Influences on Reliability and Performance of AU Based SHM Systems, Requirements and Approach for Detection Performance Assessment

Christian STOLZ *, Andreas HABERL *, Christoph MEISNER *
* EADS Deutschland GmbH Division Cassidian, Manching, Germany
christian.stolz@cassidian.com

Abstract. Recent trends show an increasing need for prognostics and lifetime estimations for damage critical structures in various industries. Military aviation is a major application area for Structural Health Monitoring (SHM) systems. Out of numerous SHM approaches being under investigation, sensor-based Acousto Ultrasonics (AU) systems which use guided waves for damage detection have great potential of meeting the future needs of autonomous life prognostics. Besides the technical development and integration of such systems, ways for the aeronautical certification are explored.

The reliability of SHM systems is a key issue for certification. Common understanding for assessing the performance and reliability in terms of damage detection is needed. Therefore the Probability of Detection (POD) is a major indicator. Existing approaches used in the field of Non Destructive Testing (NDT) based on testing are not fully applicable to POD assessments due to restricted test efforts. Simulation based assessments will help to minimise the test effort to an acceptable scope. Simulation techniques need basic knowledge of wave propagation physics, material properties of monitored structures and influencing parameters. Detailed validation of the simulation techniques tools is necessary to satisfy the certification issues.

This paper presents reliability aspects in the context of sensor-based AU systems. Several influencing parameters on system reliability are investigated. Effects of sensor integration, environmental conditions and guided wave modes on detection reliability are considered.

1. Introduction

SHM systems in military aircraft are in operation for several years and more sophisticated systems are developed. The system capabilities have been enlarged from simple usage monitoring to modern fatigue and damage monitoring [1]. Nowadays technologies like Prognostic Health Management, Integrated Vehicle Health Management and Integrated System Health Management are based on SHM data and provide various capabilities for in-service solutions in order to maximize the security, availability and mission success. In-flight monitoring, onboard data processing, health assessment and prognostics are important capabilities for future unmanned aircraft systems and support online mission management.

During the past years several damage detection systems are developed. Next to the simple automatization of a non-destructive method, these systems provide data for modern prognostic health management systems. Still, a key area of development is the Verification & Validation (V&V) method leading to the qualification and certification, where reliability of SHM systems is a key issue. As a major performance indicator, the POD is playing an important role during the certification. Due to modern airframe design principles, like damage tolerance design, reliable monitoring of defined damage sizes is required and needs to be certified.

2. Comparison between SHM and NDE

In course of validating the performance of sensor-based SHM systems, the POD is essential information. Reliable statements about the success of damage detection are necessary. Only that way, the economical use of SHM systems is possible. In order to provide a universal assessment for certificating sensor-based SHM systems, the term POD requires an exact definition.

In the past, POD was already relevant for evaluating NDT methods being used for manual maintenance activities. In conventional NDT assessments, POD is a function of damage size. As exemplary shown in figure 2.1, the POD-curve (solid line) is computed based on experimental hit/miss data (black dots). Also confidence limits (dashed lines) are depicted, which confine the most likely area in which the true POD might be. For calculating a statistically reliable POD curve, a large number of samples and consequently a lot of test effort is required.

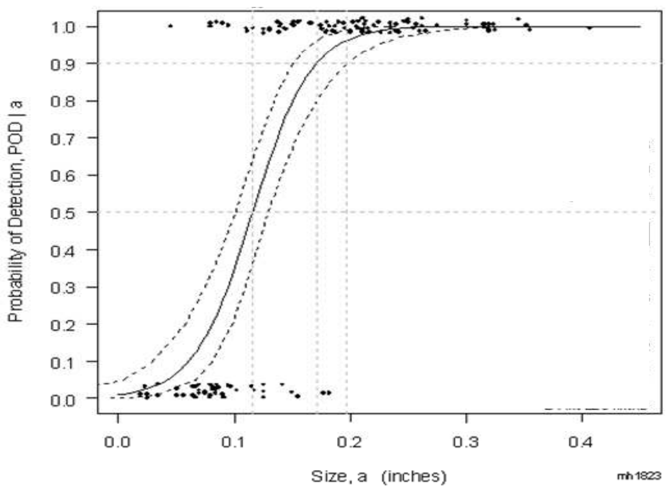

Figure 2.1: Conventional POD curve for NDI assessment [5]

The performance of a NDT system is commonly considered as acceptable, when there is a 95% confidence to detect at least 90% of damages (90/95 POD). This 90/95 limit is confirmed as an adequate validation argument by further NASA and military papers about NDT [5, 6].

Sensor-based SHM systems being partly integrated into aircraft structural components provide similar outputs as manual NDT methods (e.g. hit or miss, damage sizes). Therefore, NDT performance assessments are considered as useful reference when defining the term POD for sensor-based SHM systems.

However, additional requirements have to be taken into account. From the economical point of view, it is necessary to reduce test efforts whereas the number of samples does not decrease. Model assisted performance assessments have great potential to satisfy this requirement.

From the technical point of view, an autonomous system might produce invalid data. In the case of sensor-based SHM systems, the four different system outputs depicted in table 2.1 have to be regarded [3].

	Damage present	**No damage present**
Damage indicated	True-Positive (TP) = HIT	False-Positive (FP) = FALSE CALL
No damage	False-Negative (FN) = MISS	True-Negative (TN)

Table 2.1: Possible system outcomes [3]

Sensor-based SHM systems use a criterion for the indication of damage. This criterion is a threshold value referring to allowable signal deviations before damage is indicated. Since the chance of a hit can be increased at the expense of a higher false call rate, this threshold value is a compromise. The POD shall satisfy the 90/95 limit (see figure 2.2) whereas the False Positive rate provides a 95% confidence that the chance of false calls is below 10% (10/95 FP rate, see figure 2.3).

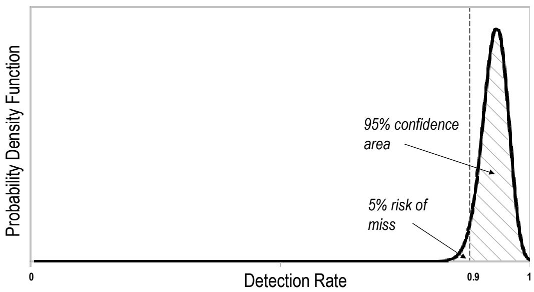

Figure 2.2: Exemplary probability density function for detection rate

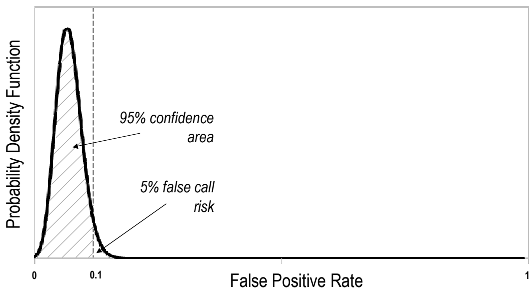

Figure 2.3: Exemplary probability density function for false calls

Binomial approaches serve to determine the confidence bounds. The confidence intervals according to Clopper and Pearson are considered as adequate hence they depend on the sample size and can be related to the binomial distribution. The confidence intervals as described above shall be calculated separately for different damage sizes. This is because large damages are more likely to be detected than small ones. Since a large number of samples might contain numerous different damage sizes, classification of sizes shall be performed. Each size class shall at least contain 29 samples. For theoretically satisfying the 90/95 criterion according to Clopper and Pearson, 29 hits out of 29 trials are necessary. The resolution of the POD curve is further depending on the number of size classes [2].

From a global point of view, the POD definition shall be applicable to all sensor-based SHM systems providing either binary (hit/miss) or quantitative (size, position) outputs. The POD definition shall further not be limited to Acousto Ultrasonics.

3. Overview Boundary Conditions

Structural components face several changing conditions which affect the behavior of ultrasonic wave propagation. Static influences like assembly conditions, or strains due to pre-loads of a structure (e.g. wing attachment) as well as dynamic influences such as vibrations or changing loading conditions (e.g. maneuvers, variable fuel mass) have to be taken into account [11].

4. Environmental Conditions - Requirement Definition

SHM systems typically consist of several components, installed in different locations within the aircraft. All components of the measurement system have to remain functional during the useful life of an aircraft. In order to guarantee operational functionality, the different components have to be tested in advance according to their field of application. These tests have to be done for each single component separately as well as for the whole system.

Aircraft, especially military aircraft, operate under harsh environmental and application conditions. An overview of these parameters and standards for development of a specification and certification tests is illustrated in [7], [8] and [9].

In the first step, the overall requirements of the SHM system are defined according to type and field of application of the aircraft. A summary of this process is illustrated in figure 4.1.

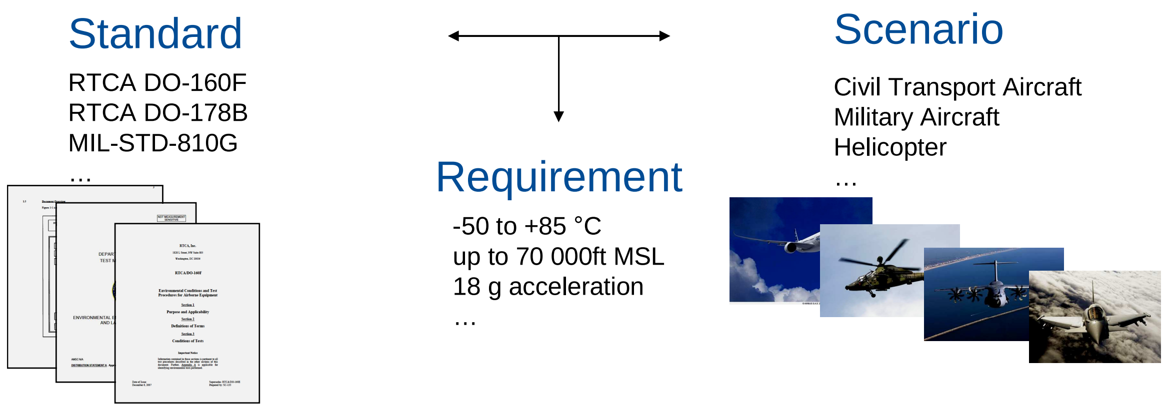

Figure 4.1: Requirements of a SHM System

A summary of typical requirement areas/topics according to [7] for airborne equipment is illustrated below:

- Temperature and Altitude
- Temperature Variation
- Humidity
- Operational Shocks and Crash Safety
- Vibration
- Explosive Atmosphere
- Waterproofness
- Fluids Susceptibility
- Sand and Dust
- Fungus Resistance
- Salt Fog
- Magnetic Effect
- Power Input
- Voltage Spike
- Audio Frequency Conducted Susceptibility
- Induced Signal Susceptibility
- Radio Frequency Susceptibility
- Emission of Radio Frequency Energy
- Lightning
- Icing
- Electrostatic Discharge (ESD)
- Fire and Flammability.

Besides the definition of requirements due to aircraft type and field of application, the specific installation location of the SHM equipment within the aircraft is affecting the performance of the SHM system. It has to be distinguished between equipment which is installed in a temperature and pressure controlled area inside the aircraft and an area outside the aircraft, which is exposed to the surrounding weather conditions as well as to in-service equipment used during aircraft operation (e.g. de-icing fluids, jet fuel, etc.) [7].

For qualification of the SHM system the requirements cannot be investigated separately. During aircraft operation, there is always a combination between different effects. A typical example is increased temperature with mechanical loading during or after temperature test.

For certification of airborne equipment all necessary circumstances have to be identified and tested in advance. A large number of coupon tests (basic level structural tests) has to be tested to investigate the different effects separately as well as in combination. This process is expensive and time consuming due to the large number of requirements.

Considering the high number of physical parameters, coupon testing becomes very costly, especially if the interaction of the different parameters has to be taken into account. For evaluation of all the parameters the model assisted POD (MAPOD) approach is very promising. MAPOD uses amongst others physical models to simulate the wave propagation within the structure. The validated model can be used to decrease the experimental effort, especially considering the interaction between different effects.

5. Overview physics and tests

For military aircraft operations the Acousto Ultrasonics (AU) Method is a promising approach to monitor the structural health of the aircraft.

The AU Method utilizes piezoelectric transducers, which are permanently applied to the structural component. These transducers generate guided waves, propagating within the boundaries of the structure. These waves show high sensitivity to structural damages of the component. By comparing a pre-recorded baseline signal without damage with a current measurement, the signal deviations can be used to determine if damage has occurred or not. A flowchart describing the process of damage detection is illustrated in figure 5.1.

If damage has occurred to the structural component, the propagating waves interact with the damage and changes in the received signal can be recognized (e.g. amplitude reduction, phase shift and mode transformation). The physical behaviour of the guided waves is used to identify the defect utilizing algorithms like Damage Index, Ellipse Method, Time of Flight, etc.

If the system has detected damage, parameters like size and location can be used to define the severity of the defect. This data can be utilised during aircraft operation to draw conclusions on the structural health of the aircraft. Mission planning as well as maintenance planning can be adapted based on current health data.

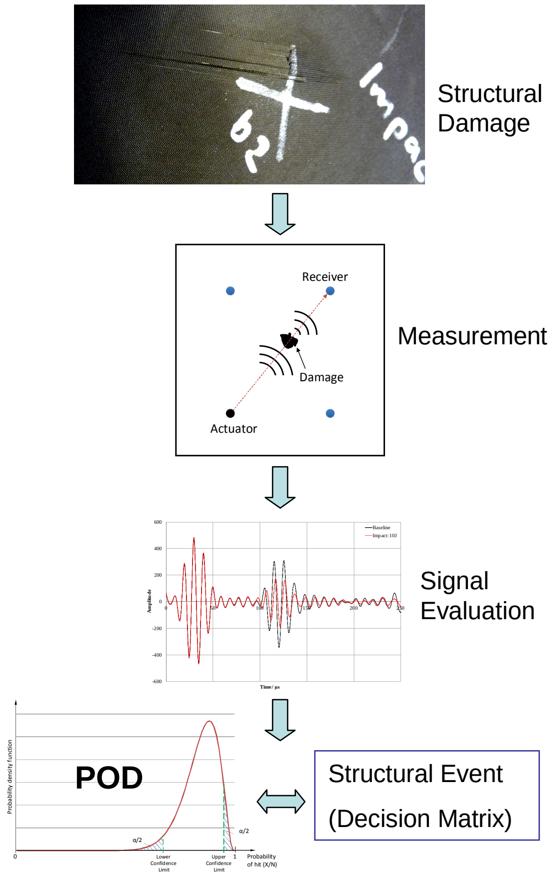

Figure 5.1: Acousto Ultrasonics Method used for damage detection [10]

Guided waves show a high sensitivity to physical parameters (compare [10, 11, 12]):

- Material of the structural component
- Shape and geometry of the structural component
- Environmental conditions [12]
- Damage size / type [10, 11]
- Sensor integration
- Loading of structure [11]
- Assembly state of structure
- Actuation Frequency/Amplitude [10, 12]
- Wave Mode [10, 12]

Considering the whole SHM system, not only physical parameters influence the damage detection capabilities. Also reliable algorithms and system components are necessary to evaluate the wave signals to achieve sufficient damage detection performance.

For exemplary illustration of the effects of environmental conditions, the following paragraph is focused on the effect of temperature on the wave propagation. Figure 5.2 shows influence of temperature on the symmetric S_0-Lamb-Wave-Mode propagating within a flat composite plate.

The test setup consists of a 3 mm quasi-isotropic composite plate with surface bonded PZT-Transducers. The composite plate is heated from 20 to 60 °C in steps of 5 degree in a humidity and pressure controlled oven. The signals are generated during heating utilizing the pitch-catch method (one transducer serves as actuator, another transducer as sensor). It can be observed that propagation speed and amplitude of the symmetric S_0-Mode is decreasing with increasing temperature due to changing material properties of the composite laminate. Regarding typical damage detection algorithms like Damage Index or Ellipse Method, the change of the signal significantly influences the damage detection capabilities. For in field application compensation techniques becomes inevitable to guarantee stable and reliable measurements.

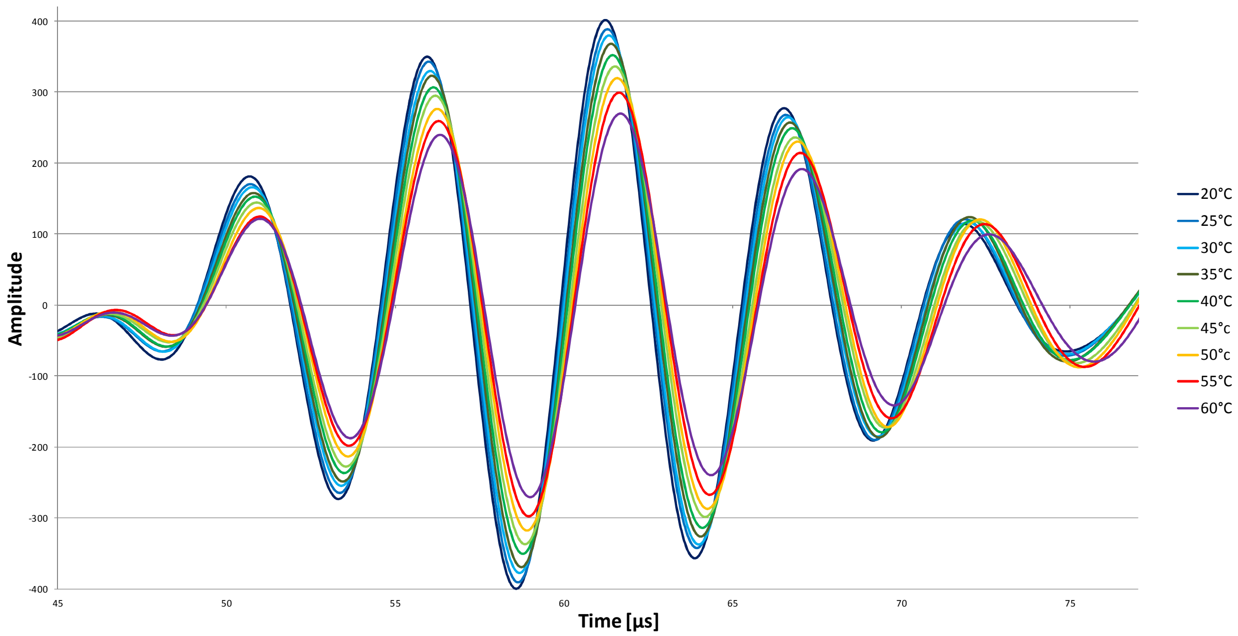

Figure 5.2: Propagation of the S_0 Lamb Wave Mode with increasing temperature [12]

The choice of adequate baseline data and determination of allowable instants of time when damage monitoring can be performed is an essential task with regard to future applications of such systems.

That means, the baseline data for AU measurements shall represent the condition of the structure during later damage monitoring as realistic as possible. Changing conditions shall be taken into account by post-processing of sensor data, e.g. by applying compen-sating curves.

6. Summary

Damage detection systems based on Acousto Ultrasonics method, which use guided waves for damage detection have great potential of meeting the future needs of autonomous life prognostics. Certification and qualification of its performance are key issues for the future usage of damage detection systems. In this paper requirement areas and typical influencing parameters on damage detection capability are discussed. Model assisted POD (MAPOD) is assumed to be an approach for efficient certification. Validation of basic physical models to simulate the wave propagation within the structure is a mayor issue for future developments and certifications.

7. References

[1] C. Stolz, M. Neumair. Structural Health Monitoring, In-service Experience, Benefit and Way Ahead. Int. Journal of Structural Health Monitoring, Vol. 9 (3). 2010.

[2] E.R. Generazio. Design of Experiments for Validating Probability of Detection Capability of NDT Systems and for Qualification of Inspectors. NASA Langley Research Center. March 2009.

[3] B. Eckstein, C.-P. Fritzen, M. Bach. Considerations on the Reliability of Guided Ultrasonic Wave-Based SHM Systems for CFRP Aerospace Structures. 2012.

[4] A. Boomsma. Confidence Intervals for a Binomial Proportion. Department of Statistics & Measurement Theory University of Groningen. December 2005.

[5] MIL-HDBK-1823A. Nondestructive Evaluation System Reliability Assessment. April 2009.

[6] NASA-STD-5009. Nondestructive Evaluation Requirements for Fracture Critical Metallic Components. September 2008.

[7] RTCA, Incorporated. RTCA-DO-160F: Environmental Conditions and Test Procedures for Airborne Equipment. Washington, DC 20036-5133, USA. December 2007.

[8] RTCA, Incorporated. RTCA-DO-178B: SOFTWARE CONSIDERATIONS IN AIRBORNE SYSTEMS AND EQUIPMENT CERTIFICATION. Washington, DC 20036-4001, USA. December 1992.

[9] DEPARTMENT OF DEFENSE USA: Mil-Std-810G: ENVIRONMENTAL ENGINEERING CONSIDERATIONSAND LABORATORY TESTS. October 2008

[10] C. Meisner. Monitoring of bonded repaired Composite Structures with Manufacturing and Operational Damages. Manching, Germany. April 2013.

[11] A. Haberl. Probability of Damage Detection of Carbon Fiber Composite Structures under Assembly Conditions and Mechanical Stress. Manching, Germany. September 2012.

[12] A. Heide. Anforderungen und Einflussfaktoren eines Messsystems zur Schadensdiagnose von kohlefaserverstärkten Strukturen mittels Lamb-Wellen. Manching, Germany. October 2013.