APPROACH TO THE TECHNICAL QUALIFICATION OF A SHM SYSTEM IN TERMS OF DAMAGE DETECTION IN AEROSPACE INDUSTRY

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ABSTRACT

In the aeronautic industry, mature processes exist to reliably assess and qualify conventional inspection techniques such as handheld ultrasonic inspections via phased array. Standards and specifications define the procedure to be applied and followed by the evaluators to analyse the inspection performance in terms of damage detection and reproducibility of the results, commonly referred to as probability of detection (POD) and probability of false alarms (POFA). In SHM little in terms of such a technical qualification process either exists nor is approved to reliably assess the different SHM technologies available in terms of their performance. Without such a defined process, SHM technologies will never be able to make the final step into application confirming a technology readiness and being finally accepted by the aeronautic authorities. In this paper a conceptual study is presented where a possible qualification process transfer is investigated for a conventional NDT procedure based on a Lamb-wave based SHM system.

Keywords: SHM, aerospace, damage detection, POD, Lamb-wave
INTRODUCTION

When developing a SHM technology for aeronautical applications requirements of given application scenarios on aircraft level have to be met resulting in benefits for maintenance, availability or design enhancement. An extensive set of requirements like assessment capability, self-diagnostic capability, durability for 30 years of operation, repair-ability, maintainability, manufacturing compatibility or airworthiness regulations needs to be fulfilled in order to achieve the technology readiness and maturity of the technology [1]. Reliability in terms of proof of damage detection capability is the keyword in order to push a new inspection measurement method into application, whether in aeronautical or in any other industry. Detection capability in non-destructive testing (NDT) is mostly referred to the probability of detection (POD) curve, the associated critical flaw size (a90|95) and the probability of false alarms (POFA).

The aim of this paper is to focus on the technical qualification requirements of a Lamb-wave based SHM system in terms of damage detection capability coming from NDT qualification process aspects on the one hand and current research activities and approaches in the frame of POD for SHM on the other.

PARAMETER IDENTIFICATION

Reliability

Inspection techniques, in NDT as well as in SHM, must provide a qualified procedure to ensure the reliability of the measurement method. Since the importance of the reliable proof of measurement capability became clear, the ASNT Reliability Studies Committee was established in 2002 [2,3] resulting from productive and motivating interactions among participants in the 3rd European-American Workshop on Reliability of NDE and Demining and in terms of gathering, analysing and defining further improvements related to the reliability formula

\[ R = f(\text{IC}) - g(\text{AP}) - h(\text{HF}) \]  

According to formula (1), the reliability of an NDT system applied is the sum of functions of:

1. IC, the Intrinsic Capability (generally considered an upper bound) or the hypothetical optimal performance of an NDT technique based on the governing physical principle;
2. AP, the effect of Application Parameters, such as access restrictions, surface conditions, and material and flaw vagaries which reduce the capability of the NDE system, or the degree to which an applied NDT system achieves its intended purpose, excluding human factors. It is defined in the context of the specification of expected application parameters;
3. HF, the effect of Human Factors, generally reducing the capability or effectiveness further and presenting physical and cognitive elements which impact performance of the NDT system [4].

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The reliability formula summarizes in an analytical way the general influencing parameters in terms of inspection reliability. Interpreting the formula visually via the probability of detection the addends shift the POD curve from “ideal” to “really measured” (as shown in Fig. 1) and thus create the well-known shape of the curve.

Fig. 1: Graphical Representation of NDE reliability formula (adapted from [4])

**Accuracy: Trueness & Precision**

One major requirement in providing a reliable inspection technique, whether in NDT or in SHM, is the reliability and reproducibility of the data outcome. It is to be proven that the inspection can fulfil its measurement with a sufficient reproducibility that implies an adequate accuracy. The general term accuracy refers to both trueness and precision. (as shown in Fig. 2). They describe the accuracy of a measurement method and depend on different factors, random and systematic errors. The term accuracy was at one time used to cover only one component trueness, but it appears plausibly that it should also imply the total displacement of a result from a reference value caused by random as well as systematic effects.

Fig. 2 Visualization of high trueness and high precision (left), high trueness, but low precision (middle), and low trueness, but high precision, in analogy of a dart game [5]

Errors due to, for example, uncalibrated measurement equipment cause a constant or proportional offset of the measurement outcome. These systematic errors affect the trueness of the mean value.

In case of insufficient preparation or knowledge of the possible outcome, the extent of the trueness might be overlooked by the inspector/executor. The precision of the inspection measurement is affected by unavoidable random errors inherent in every measurement procedure and comes from random processes in the measurement equipment. Since the factors that influence the outcome of the measurement cannot be fully controlled, the variability has to be taken into account. [6]
Repeatability & Reproducibility

In order to overcome untrue results attention shall also be paid to adequate repeatability, which means the precision under repeatable (equal) conditions and reproducibility, and reproducible (but different) conditions. The outcome describes the minimum (repeatability) and the maximum (reproducibility) variability in results [7].

Probability Of False Alarms (POFA)

The control of false call rate is clearly of higher importance and relevance in the SHM field, whether regarding the acceptance and the convincing of the inspection method to authorities and OEMs that are critically examining the technology or the higher set of influencing parameters (environmental, etc.) when applying the SHM system (e.g. Lamb-wave based) permanently to the structure. In Airbus, NDT measurement methods must have a probability of false alarms (POFA) of less than 3%. This value should be transferred to the SHM domain and depending on its spot of application even reduced when fulfilling higher measurement responsibilities.

VERIFICATION OF INSPECTION TECHNIQUES IN AERONAUTIC INDUSTRY

NDT Methods

At Airbus [8], the reliability of NDT methods is described with respect to the threshold of detection and the false calls rate. Based on a specific application the overall performance is measured against the aims of that inspection. Two aspects are considered:

- Effectiveness: this considers the overall performance of the method, which takes into account all parameters of the component to be inspected and all inspection parameters;
- human failure (failure of equipment and diagnosis).

In order to calculate the POD of the inspection method two statistical methods are mainly preferred for considering the POD analysis:

- hit/miss analysis (according to [9], adapted from [10,11]);
- signal response analysis (according to [9]).

Alternative analysis approaches (e.g. the “29/29”-method) are authorized to be applied when data cannot be processed by using the two methods mentioned. In general, the choice and reasons for an alternative application should be clearly identified and explained. The 29/29-method is based on a binomial approach [12, 13] and requires the successful detection of 29 identical damages of the same size out of 29 inspections. If one or more inspections fail, it is statistically determined how many inspections have to be conducted to accomplish a POD of 90% (see Table 1). Both POD analyses based upon Berens, the hit/miss analysis and the signal response analysis, have limitations in their field of application depending on the available data being the following that:
Data contain hits only,
The tendency “the greater the defect size the higher the probability of detection” is not given.

In case that one of these limitations is fulfilled both analyses would lead to false results and thus cannot be used.

**Table 1** Number of trials versus permissible number of failures

<table>
<thead>
<tr>
<th>No. of inspections</th>
<th>No. of misses</th>
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<tbody>
<tr>
<td>29</td>
<td>0</td>
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<tr>
<td>46</td>
<td>1</td>
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<td>89</td>
<td>4</td>
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<td>103</td>
<td>5</td>
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Conclusions for SHM Methods

For SHM, the Berens methods seem to be not convenient because both limitations have to be assumed in this case (e.g. if a SHM sensor fails, the defect size may grow towards infinity, and nevertheless, the SHM sensor will not detect the defect.). One alternative in order to determine POD for local SHM systems might be the 29/29-method. In 2007, a POD analysis of the Comparative Vacuum Monitoring (CVM™) technique was performed at Airbus using the 29/29-method. It has to be noted that these POD analyses were the first which have been performed within Airbus in order to qualify the crack detection capabilities of a SHM technology. This approach worked in a reliable manner for local SHM technologies but might not be applicable for global SHM technologies.

For global SHM systems, the determination of the detection capability is much more complex and there is a number of influencing parameters whose role of interaction must be understood. Besides the complexity, the POD analysis in this case must perhaps lead to another significant value than the “known” 90/95.

**APPROACHES FOR SHM POD IN TERMS OF LAMB-WAVE BASED SYSTEM**

In principle, it is agreed that the reliability of a SHM measurement method cannot be straightforwardly transferred from the principles applied with conventional NDT methods. Reliability in SHM differs from NDT reliability [14] through the different operational modes basically, which are handheld temporarily pressed on for the NDT inspection and permanently attached to the structure for SHM. This permanent application requires the consideration of the respective more influencing parameter [15] leading to consideration of requirements that are related to the system installation, system application, system integration, system maintenance and that are relevant for the structural item as well where the system is attached to (see Fig. 3). Therefore, the reliability assessment and acquisition of POD data in SHM, especially for Lamb-wave based SHM systems is not that simply exploitable as for handheld NDT systems (i.e. phased-array).
The recently published US patent [16] assigned by Accellent Technologies presents a method to determine the POD curve for a network of sensor-actuator transducer pairs monitoring and detecting damage in a grid-defined structure over the area to be monitored (see Fig. 4) and placed at respective locations. After establishing an individual path POD via the reference-based signal analysis with defined damage index for symmetric and asymmetric wave modes and through alternating the signal path lengths and damage locations as well as the position and extent of the detectable damage in the structure a standard database is created containing the POD information of various transducer network designs. Based on the database the POD of the SHM transducer network is determinable whether just in one cell of the gridded monitored area or in the entire network. With the acquired data, conclusions are drawn with regard to system cost related to transducer density. Further patents deal with detailed issues regarding the signal path optimization [17], the detectable defect size [18], and the postprocessing [19, 20].
Lamb-wave based SHM requires a reference for the undamaged condition which might become problematic in case this reference has not been monitored at a structure’s life cycle onset. In this case a baseline free signal analysis might be useful and is currently investigated [21]. Also in terms of SHM POD determination, it might be very helpful since the main approaches are established on the reference-based method so far.

POD SIMULATION

Since the damage detection capability assessment of (Lamb-wave based) SHM system seems complex and time-consuming the idea of qualifying the inspection method through computational simulation becomes an alternative of increasing interest [22]. Recently, much scientific work has been done by using on one hand FE-based simulation [23, 24, 25] and simulation based on spectral elements [26] for wave propagation of Lamb-wave based SHM systems. The main issue here is still the “non-idealisation” of the simulation experiment and thereby to assume the correct impact of the occurring parameters and their influences.

On-going effort on using models and transfer functions to minimize the amount of empirical data is already developed since a long time ago for NDT needs and currently in development for SHM purposes. It is called Model-assisted Probability of Detection (MAPOD) and leverages both computer models and transfer functions to enable the determination of the sensitivity of damage detection systems and the effect of the changing sensitivity threshold on the number of false calls that occur as a result of implementing an NDE system while minimizing the need of empirical data [27]. The assessment of non-destructive inspection methods as described in [28] is currently updated by incorporating the process of model-assisted probability of detection evaluation [29]. A MAPOD working group [30] from the Center of Non-Destructive Evaluation (CNDE) discusses the promotion of increased understanding, development and implementation of model-assisted POD methodologies for NDT and SHM. In a case study for an acoustic SHM system the development of a respective POD curve is shown using a model-assisted strategy [31].

WAY FORWARD IN AERONAUTIC INDUSTRY

Much effort is done from the international working group on SHM within Aerospace Industry Steering Committee (AISC), established in 2006 that is constituted of the airlines, OEMs, regulatory agencies, commercial SHM suppliers, research agencies, and interested parties. The mission of the working group is to provide an approach for standardized and harmonized documentation that shall provide basic requirements to guide SHM technology development and SHM usage on air and space vehicles and shall give a baseline for other documents, which deals with SHM (e.g. MSG-3) and guidance for structural maintenance practice using SHM processes. Existing and applicable common standards specifying the structural and system-based requirements (such as [28, 32]) hereby form the baseline to this guideline document that are extended and adapted for SHM purpose [33, 34]. One major requirement is also the guidance on POD, confidence and POFA analysis as well as guideline for equipment calibration [35].

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CONCLUSION

Parameters driven by the process of technical qualification of non-destructive inspection methods have also to be seriously considered with regard to SHM technology. Further on, experimental studies for local SHM systems regarding this issue need to be performed and approaches to the determination of POD for Lamb-wave based SHM systems and model-based concepts to determine the POD while minimizing the effort have been developed that can be discussed and further validated in the context of aeronautical applications.

It is of significant importance that the technical qualification of SHM systems in terms of detection capability assessment is of decisive weight with regard to give the system its required readiness level in terms of future application in aeronautics. This will require fundamental and applied research to chart the path forward towards reliable SHM damage detection capability assessment.

REFERENCES


