Considerations on the Reliability of Guided Ultrasonic Wave-Based SHM Systems for CFRP Aerospace Structures

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ABSTRACT

Guided Ultrasonic Waves (GUW) are regarded as an effective technique for impact damage assessment of CFRP structures. Especially in the aerospace field, the introduction of such a system requires the compliance with the applicable standards and regulations. This is certainly mandatory due to safety considerations. Besides that, performance and reliability of SHM is as well of major importance to make an SHM system economically useful. Accuracy and precision of damage assessment is of high interest, which for conventional NDT methods is reflected in the probability of damage detection (PoD) and the false alarm rate. Here, the damage assessment performance (DAP) for a certain class of SHM systems is detailed as a transfer of the known PoD. The reliability analysis is an elementary step in particular in the development of SHM systems, including the inherent complexity of the utilized technique and the applicable boundary conditions.

In this paper, first considerations on this reliability analysis are presented, covering especially application dependant aspects.

INTRODUCTION

The assessment of damages after impact in CFRP aerospace structures poses an attractive application case, as the damage behaviour of such structures typically makes visual inspections difficult and causes costly NDT inspections. SHM may save downtime of the A/C and maintenance cost, given that SHM is quicker and less expensive than NDT for a particular task, but first of all provides the necessary inspection capabilities. Considering SHM as a system which is by its nature to a certain extent integrated in the aircraft structure and systems, the management of structural integrity relies the functioning of this system. Furthermore are the associated maintenance and repair cost of the A/C affected by the overall system performance and reliability. The requirements applied on such system need to reflect

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that and the development process needs to be that way, that it can provide sufficient evidence of their fulfilment.

In NDT the study of the probability of detection (PoD) is accepted as an adequate means to prove the performance and reliability of a particular test method. The capabilities of SHM can be classified by four levels according to [1]: Detection, localization, quantification, prognosis. Clearly, PoD can only be a metric for the first level "detection", while the advantage of SHM by GUW is its potential of wide area damage localisation and quantification (third level).

As impact damages in CFRP structures may be barely visible, it is ensured by design, that any damage of a certain size and related visibility, which is not detectable by the applied visual inspection scheme, is not and will never become critical. Due to the resulting no-growth design rule, prognosis is currently not of interest for CFRP structures. Instead, structural integrity is rather determined by the remaining strength and static load cases. Any allowable damage limit derived by that analysis (as stated in a standard repair manual of an A/C) is only valid for a certain area. For such a scenario utilizing a 3rd level SHM system, the performance and reliability of quantification and localization needs to be analysed.

The following of this work is a suggestion what to consider for such analysis or in the general technology development, without the claim to be complete.

PERFORMANCE AND RELIABILITY OF GUW-SHM SYSTEM

Reliability can be regarded as the probability of successful operation or performance of systems and their related equipment, with minimum risk of loss or disaster or of system failure [3]. What can be deduced from that for the basic technology part of a rather generic SHM system? First of all, reliability is determined by all parts of a system, but the hardware components themself or software code shall not be regarded in the presented work. From the definition, it appears to be necessary to define what a successful performance is. In a framework of requirements-based engineering, this is included in the system requirements, which depend on the boundary conditions the system shall be used under. This is quite important, as the used technology and the inherent system behaviour might determine what the necessary boundary conditions to be specified are. In order to get a complete and correct set of requirements, a validation takes place which needs to reveal such dependencies. Other boundary conditions are coming from the operating conditions and from the usage of the system within these operations.

A prerequisite to define a performance metric is a definition of the function of the generic SHM system: Assess size and location of damages in a CFRP stiffened shell of an aircraft, to enable subsequent damage severity assessment by comparison to a defined damage size limit for each position.

The outcome of such assessment in terms of classification can be described as in table 1, where $a_{detected}$ is the assessed damage size, a_{limit} the damage size limit, a_{real} the actual damage size. An undetected damage is treated as $a_{detected} = 0$.

In order to find reasonable values serving as metric, the reader is asked to join the following gedankenexperiment: It is ideally assumed that the probability to get a certain damage size and location as detection result in dependency of the real damage size is known for each position. Zero size is to be included as a possible result, by that the probability of detection is included.

Classification out-come	actual classification	
SHM Assessment	above applicable limit $a_{real} > a_{limit}$	below applicable limit $a_{real} \leq a_{limit}$
above applicable limit $a_{detected} > a_{limit}$	True-positive (TP)	False-positive (FP)
below applicable limit $a_{detected} \leq a_{limit}$	False-negative (FN)	True-negative (TN)

Table 1. Classification out-come.

For a given real damage size (a_{real}), the lower and upper bounds ($a_{detected|10}$ and $a_{detected|90}$) can be deduced from the cumulative distribution functions (cdf). It can be further assumed that there exists a minimum detectable damage size ($a_{min\ detectable} > 0$), with an associated probability of 90% to get a damage size greater than zero (or equivalently: $a_{detect|10}$=0). Figure 1 visualizes the assumed relations, including the cdf plots for the minumum detectable size (figure 1a)) and for one exemplary damage (figure 1b)). The shown simple curves are exemplary only, assuming a systematically deviation.

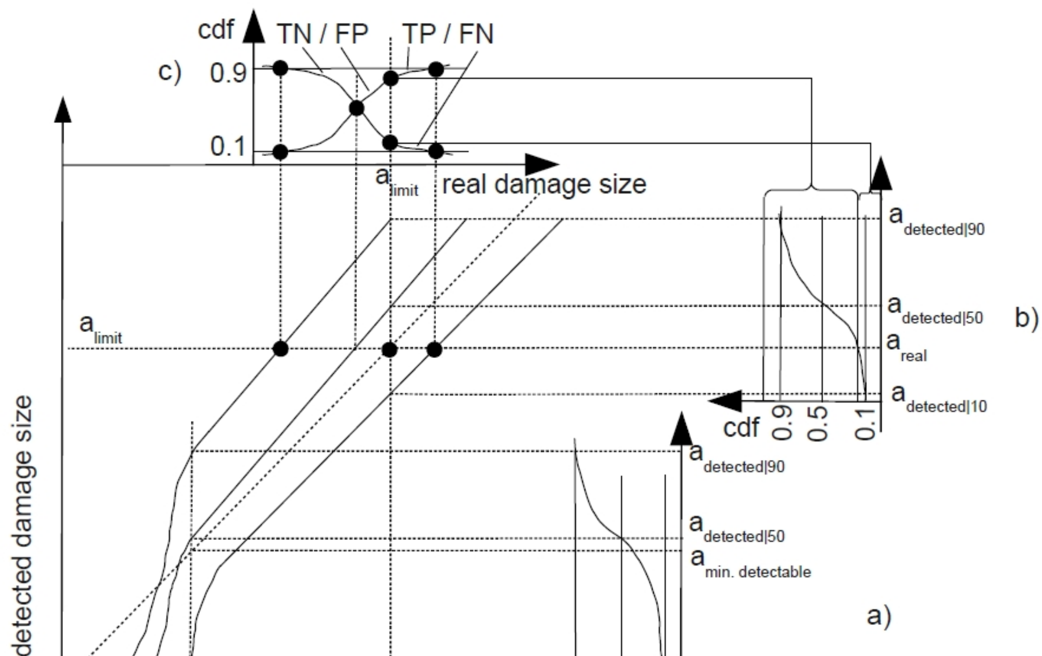

Figure 1. Damage assessment performance at one position.

In general, the classification outcome is depending on the limit value. The classification outcome over the real damage size can be derived for one limit value. Shown is the case $a_{limit} = a_{real}$, the true-negative (TN) and false positive (FP) probability can be seen in the cdf in figure 1c) for a_{real}. From the upper and lower bounds the damage size with 90%/10% true-positive/false-negative probability and 90%/10% true-negative/false-positive probability can be deduced. In any case, the 90% true-positive classification probability will be achieved at a damage size higher than the limit. In order to assure a 90% true-positive classification for a fixed given limit, a margin has to be considered, leading to an applied limit value lower than the original one.

The localisation accuracy and precision per point can be represented by a spatial probability distribution as well. As the damage limits are depending on the position, it is of interest to apply them in a conservative manner. A scheme to include the location error is not elaborated in the present work.

Summarizing the proposed damage assessment performance metrics from the presented analysis scheme, we see:

- minimum detectable damage size for a defined probability of detection
- mean assessment accuracy as the difference between $a_{detected|90}$ and a_{real}
- applicable limit value vs. design limit value
- False-positive probability for $a_{detected|50}$ and applicable limit value
- localization bound with a defined probability

over the area to be assessed and for the range of relevant damage sizes. The confidence intervals used to derive the statistical values need to be specified.

The gentle reader now might get disappointed, as it will remain unsolved in the present work by what exact methodology these metrics and probability distributions could be derived. Before thinking on dedicated experiments or statistical calculations, the factors influencing the damage assessment performance and thus the SHM system reliability, need to be determined. Any verification approach to prove compliance with the requirements for a dedicated application and system is depending on this, as well as the validation of requirements, as explained before.

In the following, the influencing factors are analysed, based on a simplified system model. Beyond the description by damage assessment performance, potential failure modes are highlighted.

SIMPLIFIED GUW-SHM SYSTEM DESCRIPTION

The following description is a simplification, targeting to include the important aspects of the technology in a generic way and explicitly does not depend on a specific algorithm – as far as possible. A basic concept of GUW-based SHM is visualized in figure 2 below. By the use of a distributed sensor network consisting of transducers at defined positions, guided waves are sent and received. One or more wave packages can be seen as probing waves, which are meant to experience a change by structural damages. The recorded signals are analysed in order to calculate damage size and location, in the broadest sense by comparison with baseline data and/or by using a priori information to assess damage indicating signal features [3]. The necessary a priori information is depending on the used technique and algorithms. They may include assumptions on the properties of the system, e.g. geometry, mechanical properties, or include assumptions on or calibration of the system behaviour, e.g. for temperature compensation, damage correlated signal features etc. It has to be remarked, that the structure is to be seen as an integral part of the system.

The functional representation in figure 3 below appears to be rather simple, but conceals the complexity of wave propagation and treats the post-processing for now as a black box.

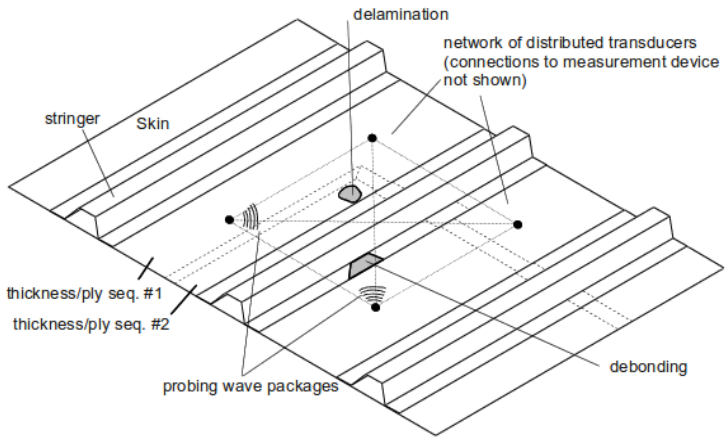

Figure 2. Schematic of simplified GUW-SHM system.

Note that state variable of temperature and humidity are field values, while the loading condition is determined by the external forces.

The transmission behaviour of the bonded transducers is among others depending on the ratio of excited wavelengths to transducers size, which results in the mode tuning effect [4]. Via the shear-lag effect the bondline thickness and shear modulus further modify this effect. Variation in the related properties, either during operation due to dependencies on the state variables or degradation, or as a deviation from the nominal system design value due to manufacturing tolerances, will change the spectral amplitude of the excited wave (and again of the received signal). Especially changes of the bondline thickness may have a significant impact [5]. Standard piezoceramics have reasonable high manufacturing tolerances as well.

Considering the wave propagation in the structure, manufacturing tolerances on dimensions and material properties may already lead to a deviation compared to nominal design values. As shown in figure 3, all state variables contribute here, i.e. by temperature and humidity dependent material properties, (thermo-) stress distribution. Throughout the service life, hygrothermal degradation can affect especially the CFRP matrix and the bondline.

The operational environment deserves careful consideration. One example could be objects in surface contact, like bumpers of passenger loading bridges or vehicles, as well as rain, snow or ice on the outer surface or any fluids, like condensed humidity, on the inside.

The wave propagation change at a delamination is primarily depending on the cross-sectional strain-distribution and wavelength on one hand and the dimension of delaminations and their depth on the other. A common feature recognized of delaminations caused by impacts are the pine-tree-profile structure and the peanut-like shapes of the delaminated areas of delaminated plies [6]. Given the large variation in the morphology of impact damages, any delamination should be considered as unique. Known phenomena are besides reflection, mode conversion and attenuation the trapping of a part of the wave energy inside the delamination area.

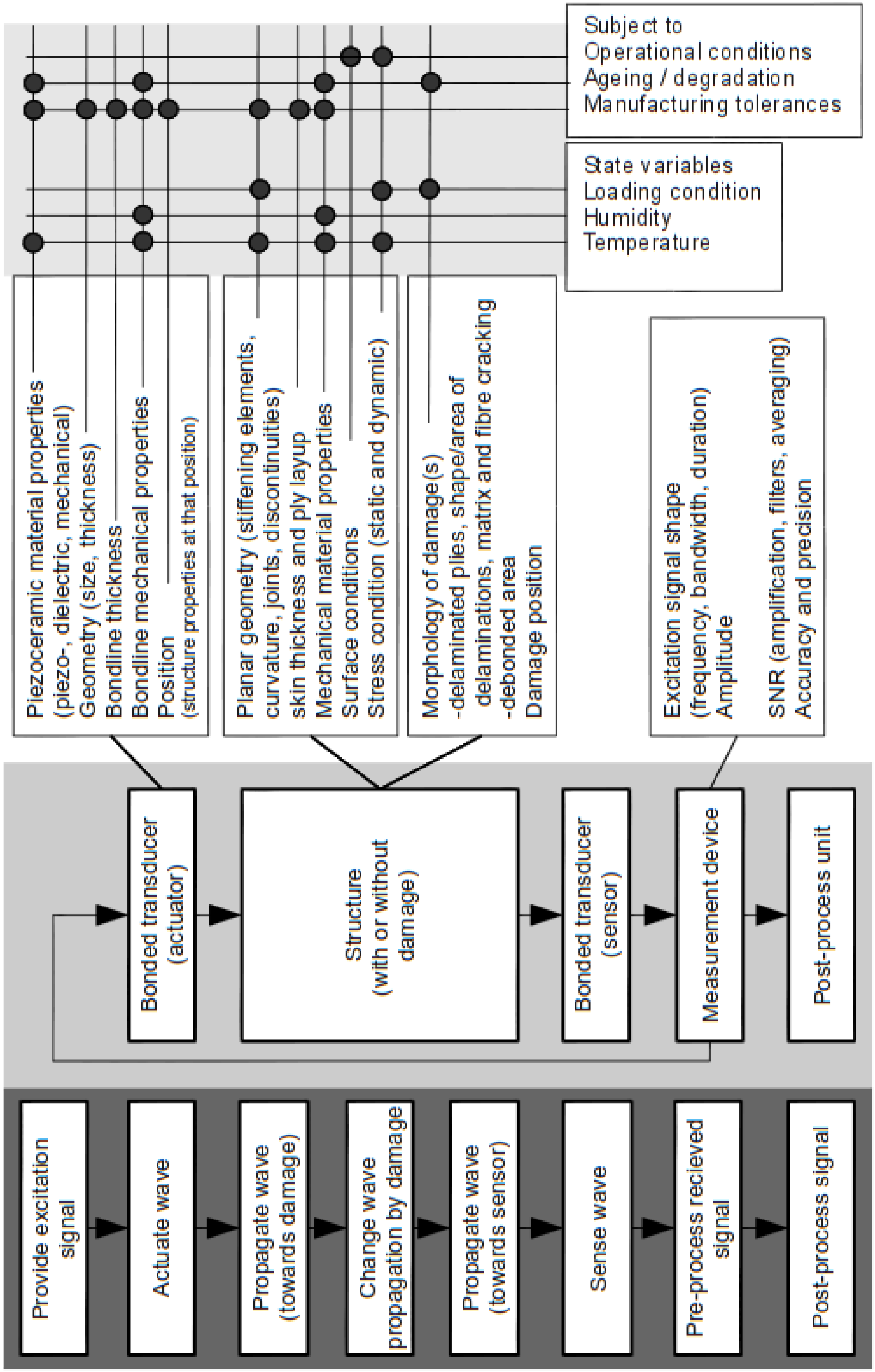

Figure 3. Functional block diagram, component block diagram, properties and influence factors.

However, reflection and amplitude reduction of the transmitted mode are widely considered as suitable effects, assumed that the wavelength is small enough. Due to the strain-distributions and wavelengths, the A_0-mode is considered more sensitive to impact damage.

POTENTIAL FAILURE MODES

Table 2 contains a summary of potential failure modes and their effect on the function of the SHM system.

Failure mode	Failure effect
tranducer breakage/debonding causes corrupted measurement data	In case of unidentified fault: Corrupted signal hinders identification of damage features, false positive detection In case of identified fault: Unavailability of signal and information
Transducer piezoelectric degradation causes loss of amplitude and/or distorted transmission	Signal changes by environmental conditions hinders identification of damage features
Transducer bondline degradation causes distorted transmission	Initial set of reference measurements/information becomes useless
Properties of wave and present damage causes insensitivity of probing waves	No damage features in signal, damage undetected or assessment error
Object on the surface causes disturbance of wave propagation	Related signal changes hinder identification of damage features and produce false-positive detections
Media on surface cause local or global attenuation of waves	Related signal changes hinder identification of damage features and produce false-positive detections
Unpredictable long-term aging of structure changes wave propagation characteristics in pristine condition	Initial set of reference measurements/information becomes useless
Overall sensitivity to the various environmental factors too high	Identification of damage features not possible, false-positive detection
Wave propagation field does not provide probing wave at damage location or Wave propagation field does not provide damage altered probing wave at sensor location	No damage features in signal identifiable; damage undetectable
Actual system properties are not matching the design values used for system design and verification due to manufacturing tolerances	System performance and reliability unknown

Table 2. Potential failure modes and effects.

Countermeasures targeting at several of the failure causes or effects are possible and/or available, but not outlined here. This is either feasible by design and appropriate design process, operational restrictions or by enhancing the evaluation software, e.g. by existing temperature compensation algorithms or transducer diagnosis methods. Nevertheless, the effectiveness and reliability of such measures then are part of the system or its boundary conditions and need to be included in the overall reliability analysis.

CONCLUSION AND OUTLOOK

A scheme to rate the classification reliability is presented, stressing the influence of accuracy on the practical value of a SHM system. Furthermore, an overview on factors influencing the reliability of GUW-based SHM systems is given by utilizing a simplified system description. Based on that, potential failure modes are compiled.

Due to the large number of influencing factors, model-assisted techniques appear to be mandatory. This is sometimes refered to as model-assisted PoD (MAPOD), however the PoD is not the solely aim here. Especially the abilities of wave propagation and damage modelling need to reflect the requirements, hence need to incorporate all necessary physical features and phenomena.

It is emphasiszed to maintain a performance integrity assurance scheme, providing means to monitor that the system operates within its design limits and still provides the necessary damage assessment performance. Transducer self-diagnosis is one part of this.

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