Challenges for SHM Reliability and Application in Aerospace Industry

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ABSTRACT

Structural Health Monitoring (SHM) methods are in focus for several years to increase availability, decrease operational costs and enable condition based maintenance during aircraft operation. Monitoring of large aerospace structures as well as monitoring of dedicated hot spot areas are typical application scenarios for SHM. In military aviation, one focus is on SHM damage detection. Several damage detection approaches are under investigation to fulfil the needs for automated structural health estimation within an aerospace environment. Sensor based Acousto Ultrasonics (AU) systems using PZT-Transducer for Guided Wave actuation and sensing are an approach which is heavily studied within scientific and aeronautic industry community.

However, these sensors and methods are still lacking wide spread in-service application mainly due to reliability and qualification challenges. This paper addresses aspects which have to be considered for SHM sensors and systems in an aerospace environment. These aspects are covering the following phases:

Design of SHM sensor network and integration into industrial development process

Implementation of sensors and system in manufacturing and assembly process

Qualification and

Certification of SHM sensors and system

To achieve a successful qualification, all aspects occurring during the complete lifecycle of the SHM System have to be addressed. For the integration of SHM sensors in the manufacturing process, sensor position deviations need to be considered as well as component tolerances within the qualification process. Additionally reliability of SHM sensors and system considering the harsh environmental and operational situation within military air vehicle has to be taken into account. To emphasise the necessary qualification efforts, examples are sketched for SHM sensor durability testing. Finally, open challenges for SHM system qualification (e.g. Model assisted Probability of Detection, MAPOD) are summarized.

1.0 INTRODUCTION

Aircraft platform availability is a key component of military capability and an important measure of the readiness and effectiveness of a force. Condition based maintenance planning and management are enablers for reducing the maintenance costs and contributing to enhance platform availability. The basis for this, are condition and health monitoring concepts, e.g. Structural Health Management (SHM) and Integrated Vehicle Health Management (IVHM). Both are some kind of System of Systems, where SHM can be implemented in an overarching IVHM system, which integrates the monitoring of all relevant functionalities of an aircraft platform. All monitoring and management concepts strongly rely on sensor data for fault detection, condition diagnostics and prognostics. For the sensor system itself, reliability is key for the quality of data and data flow.

The paper will discuss factors influencing reliability during the complete lifecycle of monitoring systems, focusing on SHM systems. For impact and damage detection, SHM system with sensor based Acousto Ultrasonics (AU) using PZT-Transducer for Guided Wave actuation and sensing are in development and will be used as a monitoring method example.

2.0 DEFINITION OF RELIABILITY FOR IVHM

"Reliability" is a widely used term thought different industries and disciplines. The term is often used together or contradictory with terms like "repeatability", "reproducibility", "variability", etc.. To detail the term "reliability" for SHM application in aerospace industry, different definitions are presented in this section. Today reliability is an import part of RAM4S, which includes the following main disciplines:

- Reliability
- Availability
- Maintainability
- Safety and Security
- Survivability
- Supportability
- Sustainability

This paper only focusses on the reliability and its relevance for SHM Systems. Other RAM4S disciplines are not fully addressed. A general definition for "reliability" for the aerospace sector is given in the SAE ARP4761 Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment:

"The probability that an item will perform a required function under specified conditions, without failure, for a specified period of time." [1]

A more specific definition of reliability of SHM systems for aircraft application can be found in SAE ARP6461 Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft:

"The reliability is measured by the probability of repeatedly and successfully observing a desirable outcome from an entity under prescribed conditions. The entity can be any observable item such as structure, system, sensor, mission, or event. A common example of a desirable outcome as sited in system engineering literature is the ability of a system or component to perform a required function under stated conditions for a specified period. Therefore, for SHM systems, reliability can involve evaluating the probability of successfully delivering an intended function under specified environmental conditions for a specified period (e.g. the maintenance free period of the system); for example, the reliability of a crack detection system can involve evaluating the probability of successfully detecting cracks having lengths greater than a specified minimum under specified environmental conditions for a specified period.

Reliability can indicate the quality of detecting the occurrence of structural events such as hard-landings or detecting the presence of faults by computing three probabilities: the probability of correct identification of faults/events, the probability of missing the faults/events (the probability of false negatives), and the probability of indicating the presence of faults/events that did not exist (the probability of false positives). An increase in the probability of false negatives of a SHM system may lead to an increase in the failure risk of the structural components monitored by the SHM system and, hence, may lead to a potential reduction in the reliability of the structural components. An increase in the probability of false positives triggered by a SHM system may lead to a reduction in the failure risk of the structural components and, hence, may lead to a potential improvement in the reliability at unjustifiable additional costs associated with "no-fault found" inspections." [2]

Next to "reliability" the term "reliability engineering" can often be read. This engineering discipline deals with specific questions regarding "reliability" throughout the system development. A definition with special focus on electronic equipment can be found in MIL-HDBK-217 Reliability Prediction of Electronic Equipment:

"Reliability is currently recognized as an essential need in military electronic systems. It is looked upon as a means for reducing costs from the factory, where rework of defective components adds a non-productive overhead expense, the field, where repair costs include not only parts and labor but also transportation and storage. More importantly, reliability directly impacts force effectiveness, measured in terms of availability or sortie rates, and determines the size of the "logistics tail" inhibiting force utilization.

The achievement of reliability is the function of reliability engineering. Every aspect of an electronic system, from the purity of materials used in its component devices to the operator's interface, has an impact on reliability. Reliability engineering must, therefore, be applied throughout the system's development in a diligent and timely fashion, and integrated with other engineering disciplines." [3]

3.0 RELIABILITY - KEY ELEMENT FOR SYSTEM PERFORMANCE

One of the central questions is concerning the rationale behind reliability: Why is reliability so important for SHM systems and their performance?

First hints are given by the definition of reliability and its probability of non-failure. But starting to assess the links and interfaces reveals the importance of SHM system and its reliability for services. SHM counts as a key enabler for Condition Based Maintenance (CBM), as it can provide the necessary information of the condition of the monitored components. This diagnostic function is the technical basis for the implementation of CBM in military aeronautics. Adding the prognostic functionalities for the components future condition will help to enable Performance Based Services (PBS). As described in [4], *"PBS is a commercial model in the capital goods industry with a specific service orientation. This model is especially interesting for this branch because aircrafts have a long-lasting life cycle. […] PBS is an innovative approach to acquisition demonstrating a cultural shift away from buying parts to buying performance." In summary, PBS requires diagnostics, prognostics, both with a high reliability and its simulation for components which cover the necessary aircraft performance."*

In [4], analyses of PBS risks are shown. The risk classes are focussing on the complete service, mainly during execution, and not only on the monitoring system. Table 3-1 is showing the identified risks of the risk class reliability according to [4].

Table 3-1: Reliability risk class in PBS [4]

Risk Classes	Execution Risk (deal assessment group)	Explanation of Risk	Main challenges
Reliability	Modified (worsened) parts reliability (and No Fault Found)	- Additional costs due to modification without any improvements - Downtime of a/c	Determination of system behaviour after modification and relevance for contractual agreements
	Platform/Product risk (maturity/experience/remaining life)	- Additional costs due to early removal - Remaining life does not equal the predicted life cycle - Forecast uncertainty	System remaining life and maturity prediction
	Scheduled checks planning	- Forecast uncertainty - Additional costs - Additional downtime of a/c	Reliable planning of scheduled checks with minimum maintenance downtime, reduced unscheduled events and optimized revenue
	System reliability	- Forecast uncertainty - Additional costs - Additional downtime of a/c	System reliability prediction

The identified risks are all linked to uncertainty, additional costs and additional downtime. The system reliability which is in focus for this paper has as a main challenge in its predictability. So, in general reliability is influencing main performance parameters of PBS, which are costs and availability.

In the context CBM as a maintenance strategy and its link to reliability, it is import to distinguish between Maintenance Benefit and Maintenance Credit: Maintenance Credit is characterized by an approval to an IVHM application that adds to, replaces, or intervenes in industry accepted maintenance practices, intervals or flight operations where the safety case has to be changed. Hereby inspection intervals can be extended or replaced. IVHM system must be certified regarding reliability, Probability of Detection (POD) and data correctness. Prognostics methods provided by the IVHM system are implemented and certified to estimate the RUL of the components. This concludes into an extended certification process. In contrast to Maintenance Credit, the safety case for Maintenance Benefit is unchanged resulting in a simplified certification process. [5]

Before starting the assessment of the life cycle phases, the concept for Verification and Validation of Maintenance Credit needs to be established. An overview of the required V&V phases to enable Maintenance Credit are shown in Figure 3-1.

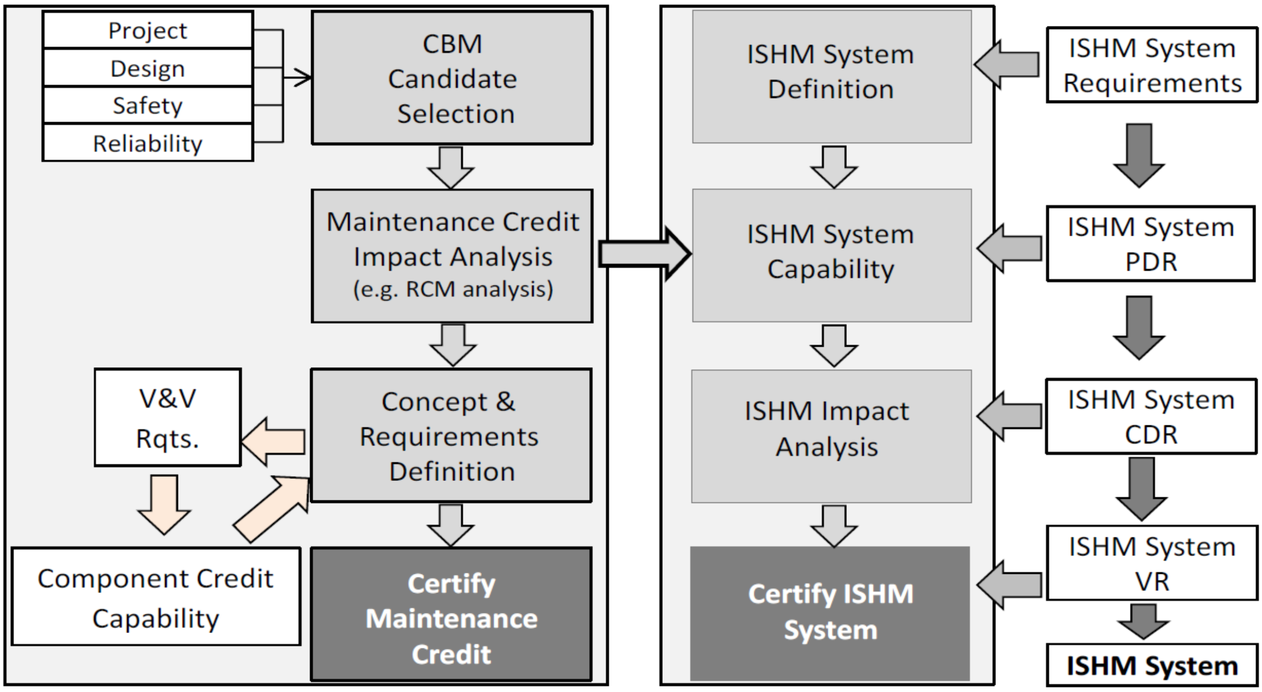


Figure 3-1: Verification and Validation of Maintenance Credit and IVHM System [5]

4.0 RELIABILITY DURING THE WHOLE LIFECYCLE

4.1 Design and development of SHM System

During the design and development phase of the SHM System, reliability is an important topic, because the basics for system reliability are set. Starting from aircraft level the requirements and architecture has to be broken down to system, sub-system and element level, see Figure 4-1. For a complete aircraft this breakdown generates a big amount of requirements and interfaces throughout different system levels which have to be managed. This requires reliable processes and tools to enable consistent data management. New methods like Model Based System Engineering (MBSE) support these processes by digitalizing the data management and enable early validation of requirements and architecture through system modelling techniques, compare Figure 4-2. This increases the reliability of the design process and decreases the risk of costly and time consuming design changes in later integration and verification activities.

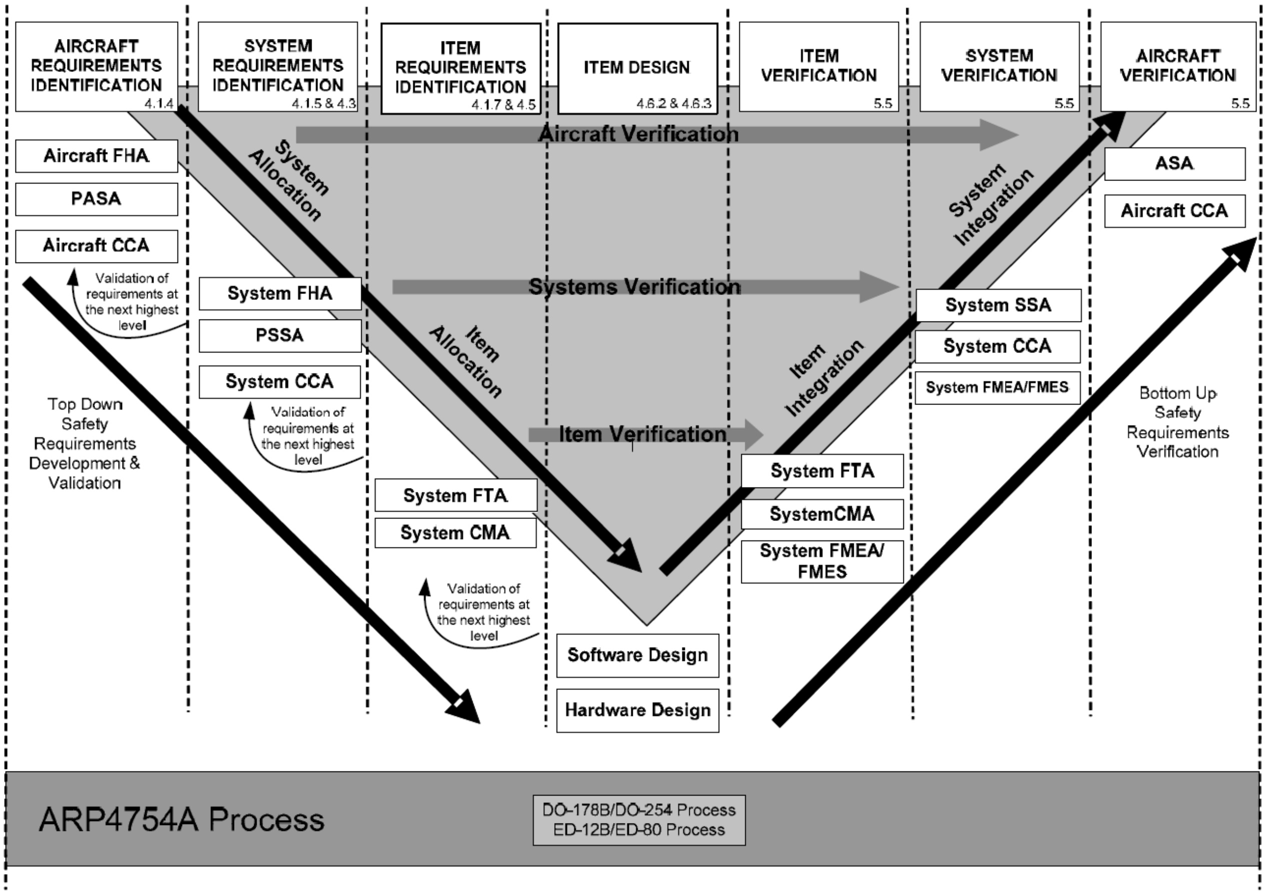


Figure 4-1: System Engineering V-Model [6]

SHM is a multidisciplinary topic involving different disciplines. This creates many interfaces throughout the aircraft resulting in a complex interface management and architecture development. Different stakeholders have to be aligned starting from structural design aspects for SHM sensor network design using CAD up to electrical equipment design and development for data acquisition and evaluation. Consequently, new and agile development processes/tools like MBSE become key to guarantee consistency and reliability through the whole SHM development process.

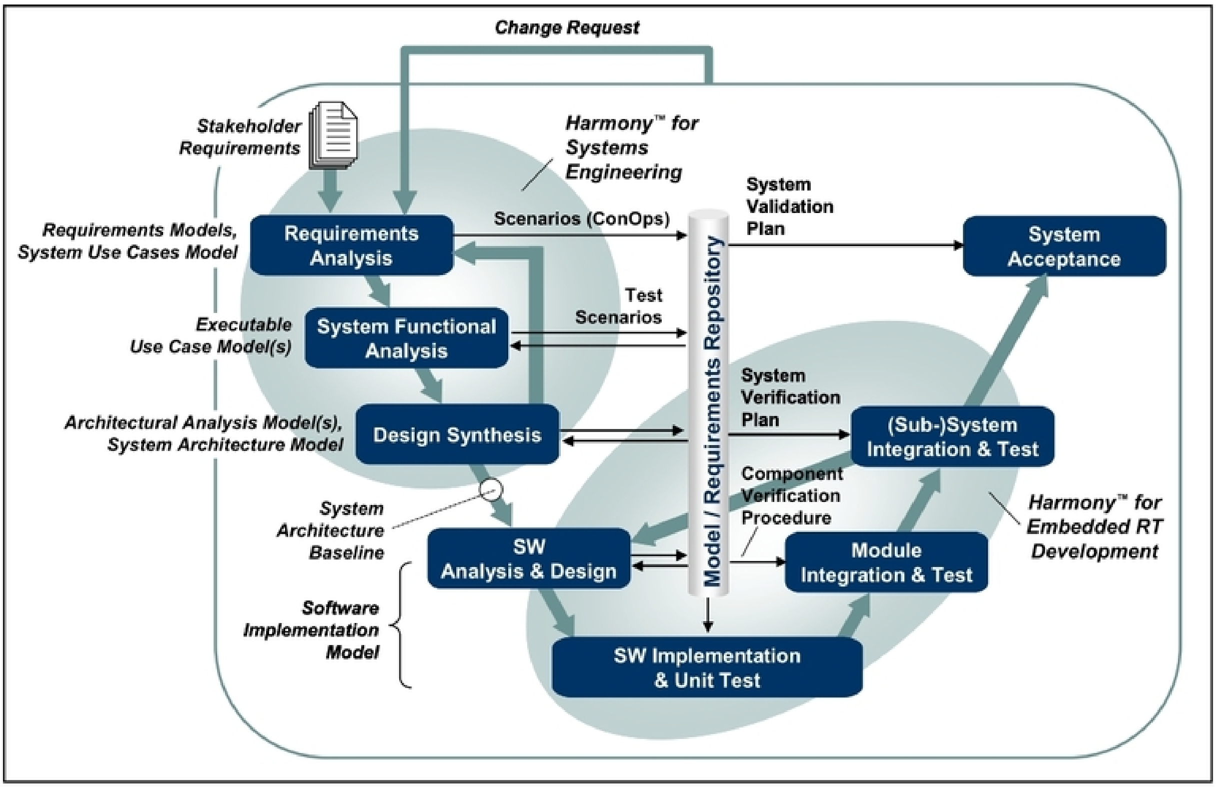


Figure 4-2: Typical MBSE Process [7]

Next to design and development methods, the identification and definition of the relevant requirements itself is crucial in this first phase. Functional and environmental requirements are depending on the system design and its physical design, as well as its installation area within the aircraft. For SHM system, which typically consists of several elements, these requirements can be multiple depending on its specific installation location. Furthermore operational, functional requirements for endurance and durability of the SHM System are defined which take into account the full service life of an aircraft. As aircraft, especially military aircraft, operate under harsh environmental and application conditions, the corresponding requirements a quite demanding.

A guidance for the definition of these parameters and standards for development of a specification and certification tests is illustrated in [8], [9] and [10]. An overview of the process is illustrated in Figure 4-3.

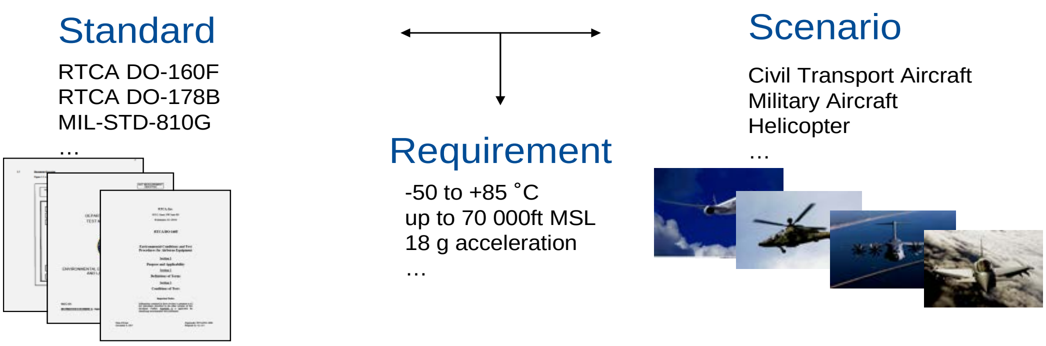


Figure 4-3: Requirements of a SHM System [11]

As already stated in [11], typical environmental and operational requirement areas for airborne equipment according to [8] can be summarized in following categories:

- 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
- Susceptibility
  - Audio Frequency Conducted Susceptibility
  - Induced Signal Susceptibility
  - Radio Frequency Susceptibility
- Emission of Radio Frequency Energy
- Lightning
- Icing
- Electrostatic Discharge (ESD)
- Fire and Flammability

4.2 Implementation and integration of SHM System

After finishing the development and design activities, the SHM System has to be integrated into the aircraft. Similar to the development process different stakeholders are involved. Looking to SHM sensor integration many topics have to be considered like: material compatibility (physical and chemical), geometric dimensions, electrical characteristics of sensors, electrical interfaces, assembly process, etc. To enable reliable integration of the sensor network not only the specific SHM sensor has to be considered.

For SHM Systems the term SHM Sensor network is more adequate. It includes specific sensors for SHM feature measurement as well as other sensors used for environmental and operational parameter compensation, the cabling routing the SHM signals as well as specific connectors to interface with the SHM data acquisition and evaluation equipment. Depending on the SHM Sensor network integration method, like secondary bonding or co-bonding, different concepts have to be evaluated to enable reliable integration.

The consequent use of classical quality measures during system implementation and integration is helping significantly to ensure the reliability of the system. Quality systems monitoring the relevant processes, parameters and results, like application of Six Sigma methods, can enhance the reliability even more.

Next to the physical SHM Sensor network integration, the overall SHM System integration has to be considered. One method is to use a simulated demonstration and verification environment including different aircraft system, the SHM System is interfacing with. This enables a flexible adaption to new requirements and overall system changes which are typical during aircraft development.

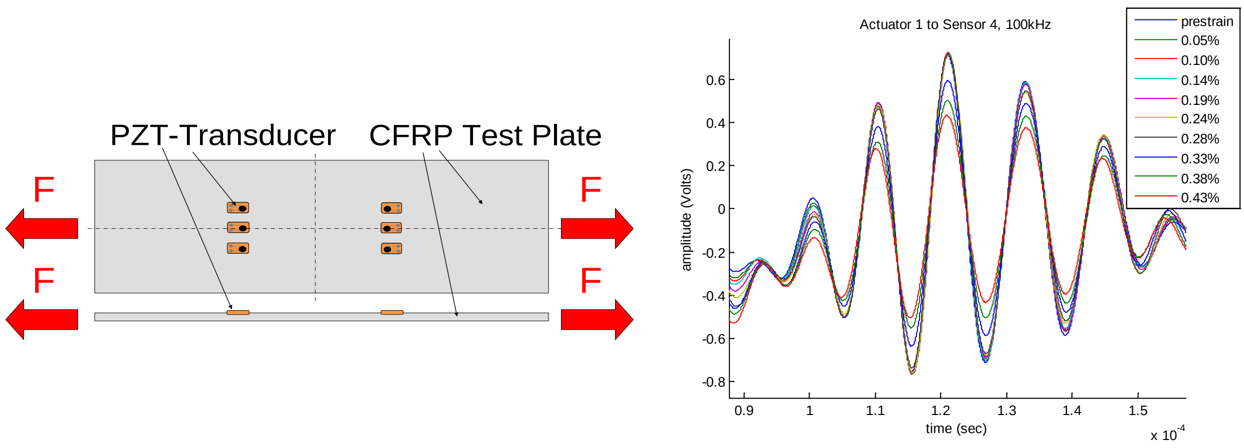
4.3 Qualification and Certification of SHM System

After and already during integration, all implemented system items and the overall system itself are verified in order to ensure the performance according to their requirements. The qualification of single system elements and the overall system is performed against the required standards. Importance needs to be given to combined effects as these influence the reliability of the system during operation.

As already stated in [12], the requirements cannot be investigated separately. During aircraft operation, there is always a combination between different effects. A typical example is changing temperature combined with mechanical loading. For certification of airborne equipment, all necessary circumstances have to be identified and tested in advance. This leads to a large number of coupon tests (basic level structural tests) to investigate the different effects separately as well as in combination. This is expensive and time consuming due to the large number of requirements. Considering the high number of physical parameters which are relevant for SHM systems, coupon testing becomes very costly, taking into account the interaction of the different parameters. The definition of these testing and certification tasks and methods is one challenge for the implementation of efficient reliability measures.

A key factor for reliability of SHM system during operation is the end-to-end testing. This essential task consumes time and effort as the full system needs to be integrated first but cannot be skipped during verification. The testing of the complete functional chain of the fully integrated system reveals shortfalls, which were not possible to identify during item or component testing and is needed to show the capability to perform according to customer’s expectations. It also can serves as a starting point for later in-service calibration testing.

An example for single element PZT-Transducer durability testing can be found in [12]. Mechanical durability testing is a typical example to verify the reliability of SHM sensors under static and fatigue loading conditions. The test coupon used in [12] is illustrated in Figure 4-4 a). This coupon is quasi-static loaded to different strain levels causing degradation within the PZT-Transducers. Typical effects of a degrading sensor on the Guided Wave signals (A0 Mode) are shown in Figure 4-4 b). During qualification of the SHM sensor, the ultimate loading conditions of the SHM Sensor have to be determined and checked against the maximum loading conditions occurring during operation.



a) b)

Figure 4-4: a) CFRP Coupon with integrated PZT-Transducers
b) Guided Wave measurements after different tensile quasi-static ramp loadings, A0-Mode at 100 kHz [12]

4.4 In-service Operation of SHM System

After verification, qualification and certification of the SHM System a constant monitoring of the SHM functions during in-service operation becomes a key feature with relevance to system reliability. For each damage detection operation, the whole SHM process chain has to be checked to guarantee reliable damage detection results. This operational monitoring of the SHM System is performed by the Build in-Test (BIT) function of the SHM System. Starting from the sensor up to the damage detection algorithms, all SHM components have to be checked by this function.

These BIT checks can be performed by different methods depending on the SHM technology which is used for damage detection. The individual BIT results of the SHM components are summarized and communicated to the next higher level function to get an overview of the overall SHM System status. As already stated in ref. [5], the BIT shall ensure that all relevant failure modes become evident to the higher level system. The results from the BIT can be compared with specified thresholds, to decide whether the respective operational function can be supported. Repeatability and reliability of the BIT is ensured by fixed test procedures and thresholds for unacceptable conditions that have been defined and verified during component and system qualification. The evaluation of BIT information is a mandatory input to continuously verify the airworthiness of the operating system. The results reported by the BIT can also be used for trouble shooting purpose to improve the SHM functionalities. Additionally some system functions can need a re-calibration from time to time, e.g. after modifications or repairs which influences the performance of the system.

An important factor of influence to the SHM system reliability is the user interface and depending of the involvement the user itself. Experience during military aircraft operations has shown that the reliability of the SHM system is influencing the user acceptance and its sensitization towards the SHM system. The knowledge of the role of the SHM system within aircraft safety, which is depending on the operational system architecture, has to be present to the operating personal, e.g. technical officers. The relevance of the SHM system has to be detailed during trainings and the knowledge with SHM system should be enhanced through an efficient in-service support. This support can result in the development and integration of enhancement updates of the SHM algorithm and system. Operational experience can also identify the need for system extensions, e.g. extension of monitoring areas, which should be taken into consideration in order to benefit from the full SHM capability spectrum.

5.0 RELIABILITY CHALLENGES

As described in last chapters, the reliability of the SHM systems is an important factor for the in-service usage of the systems and the overall aircraft. During all phases of the system life cycle the reliability is influenced by specific factors or methods. Main challenges and open research and technology tasks can be identified in the qualification phase of SHM systems. Today there are no guidelines or standards for the definition of qualification methods available. A pure coupon testing in order to test the system performance under specific environments is not enough. The combination of different environmental factors with effect on the performance has to be covered. These tests can be very costly due to the high number of physical parameters which are relevant for SHM systems. Therefore additional means of compliance, to pure testing, has to be defined and verified.

For the evaluation of all the influencing 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. A mixed approach with MAPOD and a reduced number of verification tests looks promising, but is lacking experience. Furthermore the accuracy and limitations of the simulation capabilities for SHM performance is under investigation.

Despite open issues in the qualification and certification, there is another challenge which is relevant mainly in the in-service phase. The reliability of the SHM system is mainly responsible for creation of trust in the system and its performance. Trust is necessary in the operational scenario for aircraft safety and the acceptance of the system and its results. Any shortfalls during operations, like non-availability, high false alarm rates, missing defect capability or in accuracy can decrease the level of trust and a low acceptance of the system results would be a unacceptable consequence.

6.0 SUMMARY AND CONCLUSION

This paper summarizes definitions of reliability for specific SHM applications in military aerospace industry. It highlights the effect of reliability on costs and time during development as well as during in-service application. Considering reliability aspects already during system development, the aircraft availability can be improved and the overall aircraft operating costs can be reduced. This is especially important for military application, because the aircraft and also the SHM system and sensors are facing harsh environmental and operational conditions. Consequently, all aspects occurring during the complete lifecycle of the aircraft starting from the development phase of the SHM System have to be addressed and considered. The paper shows the importance of continuous monitor (BIT) of the SHM system to ensure fully functional measurement chain. Finally, open challenges for SHM system qualification (e.g. Model assisted Probability of Detection, MAPOD) are summarized.

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