US Air Force Research Laboratory Perspective on Structural Health Monitoring in Support of Risk Management

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ABSTRACT

The US Air Force (USAF) and US Department of Defense have a long history of research and development in the exploration of on-board sensors being used for detection of damage in aircraft structures. Initial activities can be traced to the early 1980's which led to an extensive on-aircraft assessment of acoustic emission based (i.e. "passive) sensor system. In the late 1990's an effort was launched to revitalize the capability which cumulated in the "Hot Spots" program which explored the use of an ultrasonic guided wave (i.e. "active") sensor system. Each of these programs encountered challenges that have hindered the use of these technologies on fixed-wing military aircraft. This paper briefly reviews these previous efforts, present current USAF Military Standards that define Structural Health Monitoring (SHM) for fixed wing aircraft, and provide a discussion of current and future concepts for research and development to resolve these challenges and enable eventual adaptation of SHM for fixed-wing applications. It includes a summary of current initiatives within the Materials and Manufacturing Directorate of AFRL and notional thoughts on potential projects for future developments required for this capability to be applied to fixed wing military aircraft.

1. INTRODUCTION

The potential of using permanently attached sensors to aircraft structure to detect damage in the structural elements of the aircraft has been an area of significant and extensive research and development. Previous publications have detailed some of the early work that date back to the early 1980s (Hutton, et.al. 1981). Initial efforts focused on the use of acoustic emission sensors to detect fatigue cracks as they were growing in metallic structure. This led to an initial aerospace application of this approach to a large number of KC-135 aircraft in the mid to late 1980s (Bakse, 1996). Challenges in the early implementation of these monitoring systems led to a pause in research and development that was reinvigorated in the late 1990s and early 2000s.

The initial focus of these reinvigorated efforts focused on several concepts and possibilities for the use on permanently attached sensors, including the potential to replace current nondestructive inspection (NDI) process used to ensure the integrity, or safety, of fixed wing military aircraft. These efforts led to significant efforts sponsored by the Air Force Research Laboratory (AFRL) to demonstrate the potential of these sensing systems as risk mitigation for alternative methods to extend and ensure the integrity of aircraft structures. One such project was referred to as the "Hot Spot" program, which sought to use on-board sensors to detect damage in a structural application (Derriso, 2009). Though this project illustrated some of the potential of using this approach, the alternative solutions focused on materials modification were found to address the need for these structures.

A result of this effort and related research and development projects funded by the USAF indicate several major challenges remain that need to be addressed before in-situ sensors can be used to detect damage for structural applications where the inspections are driven by the structural integrity program for that weapon system. This has led to a strategic pause in the funding of applied research by AFRL to sort through the challenges and identify key parameters that need to be addressed with additional research and development before another demonstration is pursued. Some of the challenge is the differing requirements that evolve from the use of separate and distinct methods to ensure the integrity of structures, both between the different military services and between military and civil aviation. In addition, the use of embedded sensors to detect damage has significantly differing requirements when comparing fixed wing to rotary wing aircraft.

Therefore, the intent of this paper is to highlight the approach of the applied research and development efforts of AFRL in the area of SHM as defined by Military Standard (MIL STD) 1530Dc1 (https://assist.dla.mil) and contrast these to efforts being pursued for civilian applications and rotary wing

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applications. Once the technical gaps are established with clarity, possible approaches to address these gaps can be pursued.

2. DEFINITIONS FOR SHM – END USER PERSPECTIVE

The acronym SHM has been used for many differing terms, such as Systems Health Management, Systems Health Monitoring, and Structural Health Monitoring. For the scope of this paper, the latter will used. Even with this narrowing of scope, various user communities have attached definitions to the words "Structural Health Monitoring" or SHM. The recent publication of MIL STD 1530Dc1 provides clarity to the definition by stating in paragraph 3.35: "[SHM] is a nondestructive inspection (NDI) process or technique that uses in-situ sensing devices to detect damage." As it specifically defines SHM as an NDI technique, it is equally important to capture the definition of NDI which is given in paragraph 3.22 as "NDI is an inspection process or technique designed to reveal the damage at or beneath the external surface of a part or material without adversely affecting the material or part being inspected." The paragraph continues with a clear differentiation between NDI and SHM by reiterating SHM is NDI using in-situ sensors.

MIL STD 1530Dc1 provides additional clarification and differentiation between other measurements that are commonly noted as SHM in the research and development community. For example, the use of sensors to monitor loads and usage of an aircraft are described as an Individual Aircraft Tracking (IAT) system in paragraph 5.4.5 and is noted to be completely separate from a system that is used to detect damage. In addition, Structural Risk Analysis is described in paragraph 5.2.14 as an analysis that "shall determine the time beyond the design service life when the risk of loss of fail-safety will become unacceptable." This analysis is commonly referred to as prognosis when discussed within the research and development community. From MIL STD 1530Dc1, as in previous versions of MIL STD 1530, it is important to note that the management of structural risk is performed on a probabilistic basis. Paragraph 5.4.5 notes that that all "significant variables" that impact risk need to be included in the risk analysis and specifically notes this includes Probability of Detection (POD) applied to detection of flaws in various locations for the NDI and/or SHM methods being used. Figure 1 shows the typical parameters that are included in the calculation of risk.

Additional discussion of the applicability of POD is found in paragraph 5.4.3.1.2 for NDI where it states "the inspection capability shall be determined using the guidance of MIL-HDBK-1823 and as approved by the NDI team described in 5.1.6." For SHM, paragraph 5.4.3.2 states "the SHM system (if used) shall consider material, geometry, accessibility, sensor POD and resulting system-level POD when determining the SHM detection capability and monitoring intervals using processes aligned with the statistical methods described in MIL-HDBK-1823." These statements reinforce previous guidance given by the Senior Leader for Aircraft Structural Integrity that POD must be provided for an SHM system if it is used to monitor a safety of flight structure (Babish, 2009).

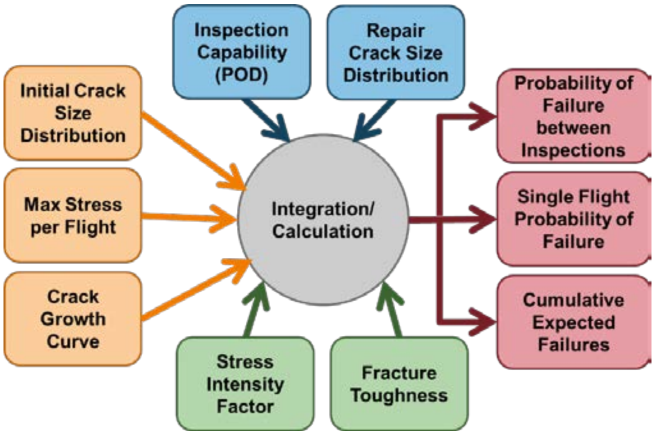


Figure 1. Common parameters used to calculate risk, such as single flight probability of failure

With the emergence of these definitions in a Military Standard, a challenge for the research and development (R&D) community is to align the concepts frequently published in research journals with these definitions. For example, in SHM-based research journals it is common to see references to Level I, II, II and IV SHM. While Levels I through III align with concepts found in NDE for detection, localization, and characterization of damage, Level IV SHM addresses prognostics which is defined as Structural Risk Analysis in MIL STD 1530Dc1. In addition, such concepts as global/local SHM and scheduled/continuous SHM are not concepts or terminology found in MIL STD 1530Dc1, but are common concepts found reported in the research literature.

Thus, if SHM is to be used on USAF fixed wing aircraft, the potential adaptation would be simplified if the R&D community recognized the terminology and definitions used by the USAF as defined in MIL STD 1530Dc1. Not using the USAF definitions increases the risk of confusion due to misconceptions when differing words are used for the same application, or when the same words have different meanings. For the remainder of this article, the definitions from MIL STD 1530Dc1 will be used when discussing SHM.

3. CHALLENGES FOR SHM – USAF PERSPECTIVE

Multiple papers and presentations have been made to reflect the challenges that need to be addressed for the USAF to implement SHM for fixed wing applications (Lindgren and Stargel, 2012, and Lindgren, et.al. 2013). These challenges include perspectives on capability development, validation, and durability. When the use of an SHM system is being considered to replace an NDI procedure, guidance on the validation requirements has been prepared by the USAF (Brausch and Steffes, 2013). It is recognized that many of these items addressed in this guidance cannot be performed using a simple process. This includes the testing of sensor and system durability in the intended area for the intended time on an aircraft. Validation using a POD study that meets the statistical methods described in MIL HDBK 1823A (http://everyspec.com) is a complex task and it has been the source of many presentations and discussions in the SHM research community.

The nature and level of difficulty of the challenges of using SHM on fixed wing military aircraft are linked to the decisions made as a result of the output from an SHM system. When this is as a direct replacement for NDI for safety-of-flight inspections, the level of capability must meet the requirement of having a POD curve to enable the calculation of risk as shown in Figure 1. When considering the need to validate the capability of the system using POD-based statistical processes defined in MIL HDBK 1823A, plus ensuring the durability of the system makes it so it does not become a maintenance driver for the aircraft, it is therefore very understandable why the implementation of SHM on fixed wing military aircraft has not occurred to date.

An additional consideration is the need to address the entire life cycle costs (LCC) of using an SHM system. While it is common to reference development and procurement costs for the system, considerations such as periodic training of operators as a function of personnel performing these tasks, maintaining and updating all technical data associated with the SHM system, plus the ability to rapidly and effectively repair any aspect of the system, including software upgrades, are commonly overlooked when analyzing the cost to implement an SHM system. This is an especially large challenge when the system is moved from a testing phase to an actual use or implementation phase. Procedures that are considered to be relatively quick and easy in a laboratory, such as a software upgrade or small modification, can take a significant effort to occur on an operational aircraft. In addition, detailed technical descriptions for installation of the SHM system are required. It is very important to recall that a key metric for fixed wing military aircraft is their availability, so any parameter that limits this metric quickly loses its pay-off in terms of lower cost to perform maintenance actions.

Therefore, many of the challenges that exist are not necessarily purely technical challenges, but are challenges in how inspection are used and where they are performed as prescribed by the structural integrity programs for fixed wing military aircraft. While some of these challenges can be addressed by technology, the focus of the technology is not necessarily on the capability of the system, but more on its robustness and ease of use. These peripheral factors can become the dominant considerations for the successful transition of new technology.

It is important to note that these operational considerations are not unique to SHM. Many technical developments have not been integrated into the sustainment of military aircraft due to factors that are not readily addressed in the R&D phase of development where the primary focus is on the ability to meet the primary objective of the technology. For this reason, it is important to consider all parameters that can affect the likelihood of new technology integration, including how the technical capability would be used relative to the operation of the military aircraft. The intended use and benefit of a capability can be referred to as its "concepts of operations" and can determine the level of performance, or requirements, that need to be validated before the capability can be transitioned to operational use

4. CONCEPTS OF OPERATIONS AND ASSOCIATED REQUIREMENTS

As mentioned previously, most research efforts for aviation-based SHM has focused on developing a capability that would be a direct replacement for current NDI methods. This can be considered as one concept of operations for an SHM system and the challenge to realize this capability are quite daunting as discussed in the previous section of this paper. However, this is only one of several potential uses of SHM.

Another use is as a test and evaluation tool, whether of the SHM system itself, or to determine the effect of a simple change in the aircraft that is not related to detection of damage. When used for this concept of operations, the desired capability for the testing activity plays into the strength of many SHM system which is to measure change as a function of time. When the testing evaluates change in only one parameter that can be detected by the SHM system and is not confounded by other factors, measurements before and after the change can be used to help understand the impact of changing that one parameter. As an example, SHM systems using ultrasound-based measurements are known to be very sensitive to load. Thus, if a modification is being tested to change the loading condition of a structural element of an aircraft, the installation of the SHM system could be used to help measure the magnitude of the change in load due to the structural modification. In addition, the testing could be of the SHM system itself to assess such factors as the ability to mount and access the sensors, or how the system could be serviced once it is installed. Most on-aircraft experiments to date fall into this category which a colleague has labeled as "flight experiments (Leonard, 2014)" which are very different from flight tests.

The ability to perform a flight experiment is greatly simplified as the desired outcome from the SHM system is less critical than if the system was monitoring a single point of failure location for fatigue cracks. This difference can be reflected in the amount of validation and durability test data required to exploit the data from a flight experiment at a much more rapid rate than using SHM to monitor for damage at a safety-of-flight location. However, it is very important to realize the difference between these two concept of operations and why the testing for the use in each is significantly different. For one, the decisions being drawn from the SHM system is integrated into a test result. For the other, it is integrated in the management of risk of structural failure. The impact of incorrect information for the latter can be catastrophic and is the reason the validation process has such a high level of rigor before the system can be used for this application.

Between these two scenarios is a third concept of operation where the SHM system is used to inform when a maintenance action is required for a non-critical structure component where failure would not cause the loss of integrity of the aircraft. When considering a building block approach to validate SHM systems for all possible concepts of operations, this intermediate step seems to be a logical next step to following the testing and flight experiments completed to date. However, these types of scenarios can be harder to identify as the impact of these situations can be less than if a need arises for a safety-of-flight location. Conversely, as the outcome is not as serious, the level of validation, while more than what would be needed for a testing application, would be less than when applying the SHM to monitor flight critical structure. The pay-off for using an SHM system in this type of concept of operations would be some form of guidance to optimize the maintenance actions required for this non-critical component.

In summary, three differing concepts of operations exist and the amount of validation testing is different for each scenario. First, if an SHM system is used for only testing purposes, it needs to demonstrate that it can measure the change of interest without being confounded by other factors during the testing period. A second concept of operations would have the SHM system monitor a non-safety-of-flight structural element and would guide any maintenance actions required for that location. A key attribute of this scenario is that failure of the component being monitored, if not detected by the SHM system, would not adversely affect the safety of the aircraft. The third and final concept of operations would have the SHM system monitoring a critical structure where failure of the SHM system to detect damage would compromise the overall safety of the aircraft. For this last scenario, it should be obvious that the validations of the capability of the system becomes much more rigorous than in the other two application.

5. RESEARCH AND DEVELOPMENT TO ADDRESS REQUIREMENTS

A challenge for the research and development (R&D) community is to recognize that many requirements that would have to be satisfied for SHM to be used for a safety-of-flight application are not explicitly given via a check-list, but are captured in the overall process to perform the transition as explained in the guidance document prepared by AFRL research engineers (Brausch and Steffes, 2013). This guidance cannot be converted into a simple check-list because the specific component can generate its own list of requirements so the process for full integration becomes application specific. This is a non-trivial challenge and leads the author to prefer to start with the intermediate concept of operations, guiding maintenance, as the first scenario for the implementation of SHM on a military fixed wing aircraft. When this occurs, the process changes from an R&D effort to a testing and evaluation (T&E) effort. The latter has much more engineering discipline and increased rigor in quantifying variables and assessing their impact on performance. In addition, the T&E must be performed for the geometry and material system of the intended application.

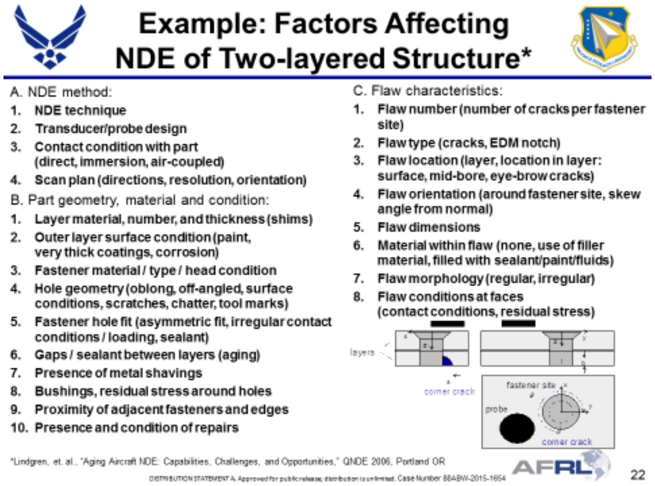
As noted previously, the T&E activity cannot only address the ability to detect damage, but must address all parameters that can affect the operation of the SHM system. This includes installation, maintenance, durability, reparability, training, documentation, and many additional related factors that will affect the life cycle costs of the SHM system. At times this can seem to be overwhelming, yet this is a consistent challenge for all technical capabilities that are new for an aviation-based application. As a slight editorial, SHM is no exception to the observation that revolutionary change is sometimes the hardest to realize.

As a strategy for evolving SHM to eventually be used to monitor safety-of-flight structure in fixed wing military aircraft, an approach is to focus on one of the largest hurdles that need to be addressed before SHM can be used for this application, namely the validation of its capability using statistical methods aligned with those described in MIL HDBK 1823A. Once there is a clear path to realize how this requirement can be met, resources can be identified to address the other hurdles, such as accelerated durability testing or other parameters that affect the life cycle costs of an SHM system.

6. FUTURE OPPORTUNITIES

When considering methods to determine POD for an SHM system, several approaches have been explored. However, as MIL STD 1530Dc1 states that the approach must be consistent with the statistical processes in MIL HDBK 1823A, the use of alternative methods have an additional drawback in that they have to demonstrate equivalence to the statistical methods of MIL HDBK 1823A with sufficient evidence to validate the new approach. With this in mind, it is clear that performing this possible validation study using empirical data becomes an extremely involved endeavor when the validation study includes all parameters that can affect the capability of an SHM system to detect damage.

The number of factors can be quite large, as shown in Figure 2 (Lindgren, et. al., 2007). A rigorous assessment of the effect of each parameter on the measurement capability for this typical structural configuration can become overwhelming when the combined effect of the parameters must be consider via a properly developed Design of Experiments (DOE) test matrix. Brute force methods that use only test data are not realistic for this very complex DOE due to the number of test samples, time to perform the testing, and the cost to complete the assessment of all factors. Alternative methods are being explored that leverage the capabilities in applied math and in using probabilistic tools to assist in the development of the DOE test matrix. By using modeling and simulation to build an understanding of these interactions, probabilistic parameters can be integrated in the DOE process that guide the selection of the test matrix parameters. In addition, as forward models mature and become validated, these models can be used to perform virtual sensitivity studies for the parameters identified via the probabilistic DOE.



Example: Factors Affecting NDE of Two-layered Structure*

A. NDE method:
1. **NDE technique**
2. **Transducer/probe design**
3. **Contact condition with part (direct, immersion, air-coupled)**
4. **Scan plan (directions, resolution, orientation)**

B. Part geometry, material and condition:
1. **Layer material, number, and thickness (shims)**
2. **Outer layer surface condition (paint, very thick coatings, corrosion)**
3. **Fastener material / type / head condition**
4. **Hole geometry (oblong, off-angled, surface conditions, scratches, chatter, tool marks)**
5. **Fastener hole fit (asymmetric fit, irregular contact conditions / loading, sealant)**
6. **Gaps / sealant between layers (aging)**
7. **Presence of metal shavings**
8. **Bushings, residual stress around holes**
9. **Proximity of adjacent fasteners and edges**
10. **Presence and condition of repairs**

C. Flaw characteristics:
1. **Flaw number (number of cracks per fastener site)**
2. **Flaw type (cracks, EDM notch)**
3. **Flaw location (layer, location in layer: surface, mid-bore, eye-brow cracks)**
4. **Flaw orientation (around fastener site, skew angle from normal)**
5. **Flaw dimensions**
6. **Material within flaw (none, use of filler material, filled with sealant/paint/fluids)**
7. **Flaw morphology (regular, irregular)**
8. **Flaw conditions at faces (contact conditions, residual stress)**

*Lindgren, et. al., "Aging Aircraft NDE: Capabilities, Challenges, and Opportunities," QNDE 2006, Portland OR

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Figure 2. List of twenty-two factors that can affect the ability to use ultrasound to detect a fatigue crack in a representative two-layer aircraft joint (Lindgren et.al. 2007).

As a representative case study of the power to use modeling and simulation, a study sponsored by AFRL addressed a very simplified scenario of detecting a fatigue crack in a representative structure using multiple sensors to measure vibrational signature changes as an indicators of the fatigue crack (Medina, et. al. 2011). Based on the configuration of multiple sensors and a constrained sample, the ability to detect damage as a function of crack size could be determined within the statistical parameters to satisfy the analysis methods of MIL HDBK 1823A. In addition, by artificially changing the functionality of sensors, including a reference sensor, the changes in the POD curve could be determined. This illustrated the effect of sensor performance decay on the detection capability of the fatigue crack. This approach can be used to evaluate scenarios when the system has a diminished sensitivity even if the sensors retain functionality. This is a known sensitivity calibration challenge for embedded systems to detect damage (Lindgren et.al. 2013).

AFRL continues to explore this approach and to identify potential scenarios where it can be statistically validated to satisfy engineering applications. This area is open for exploration and, if successful, can address the specific needs to validate an SHM system for a fixed wing military aircraft. However, this approach should have applications that extend far beyond SHM and could realize a considerable change in the development of engineering test matrices.

Once this approach is proven to be successful, which will be a significant effort, the next steps for future R&D includes addressing accelerated durability testing and a comprehensive analysis of other life cycle cost factors. Several approaches for these latter topics are being pursued in other technical domains and need to be leveraged by the R&D community focused on SHM systems. In parallel to explore the probabilistic DOE for SHM, AFRL is identifying all the additional life cycle costs that will need to be addressed and plans to prepare a document that provides insight from the fixed wing military aircraft perspective of these items and what technical gaps exist that need to be addressed with additional R&D.

7. SUMMARY

The exploration of the capability of SHM as defined in MIL STD 1530Dc1 has been underway for multiple decades and previous efforts have all encountered challenges that have prevented the use of SHM for fixed wing military aircraft as a method to replace current NDI processes. The recent publication of MIL STD 1530Dc1 provides clear definitions of SHM and the processes that must be met to validate the capability of an SHM system to detect damage when applied to a safety-of-flight structure. However, additional concept of operations for the use of SHM were identified, including as a test system and as a monitoring system for a non-safety-of-flight location, where the validation requirements may not be quite rigorous.

In addition to SHM for aircraft applications, several areas of potential future R&D are identified. A method to address a significant hurdle to the use of SHM, namely determining POD following the statistical methods described in MIL HDBK 1823A, via the development of probabilistic DOE approach will be explored by AFRL to determine if this can used, in combination with validated forward models, to simplify and accelerate the approach for determining POD. Other areas open for R&D to enable the use of SHM are being identified and will be published in future papers. AFRL will continue to explore technical developments with the objective to optimize the opportunities where SHM can be used to facilitate the safe operation of USAF aircraft.

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BIOGRAPHY

Eric A. Lindgren is currently the Nondestructive Evaluation (NDE) Technology Lead in the Materials State Awareness Branch of the Materials and Manufacturing Directorate of the Air Force Research Laboratory. Before joining AFRL in 2006, Eric worked as the Director of Nondestructive Evaluation Sciences at SAIC Ultra Image. He has over 30 years of experience in NDE research, development, transition, and deployment, including efforts to develop and deploy advanced inspection methods for aerospace applications, transitioning basic research to inspections used on USAF aircraft structures, and developing materials characterization and process monitoring/control methods using NDE technology. He earned a B.S., M.S., and Ph.D. in Materials Science and Engineering from Johns Hopkins University.