

History and Challenges for Structural Health Monitoring (SHM) for Fixed Wing Military Aircraft

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ABSTRACT

The concept of using permanently attached sensors to detect damage in fixed wing aircraft structure has been explored since the late 1970s. The types of sensing that has been explored include various acoustic, eddy current, mechanical, and strain-based sensing systems. However, to date none of these systems have been installed on Department of the Air Force (DAF) fixed wing aircraft except for experimental applications. This paper reviews past efforts within the DAF to investigate using integrated sensors to replace current nondestructive inspection (NDI) processes. The discussion of past projects cannot be comprehensive due to the large volume of literature in this field, but will cover each primary sensing modality, typical sensor types, and signal processing approaches. In addition, how the sensing techniques integrate with the DAF Aircraft and Structural Integrity (ASIP) Military Standards, such as MIL STD 1530D, is a critical attribute for sensing systems to become direct replacements for current NDI processes. The needs of fixed wing aircraft are compared to the successful implementation of sensors on helicopters to detect evolving change in rotating drivetrains.

INTRODUCTION

For the United States Department of the Air Force (DAF), the management of the integrity, or safety, of aircraft is governed by Military Standard (MIL STD) 1530Dc1, Aircraft Structural Integrity Program (ASIP) [1]. As described in MIL STD 1530Dc1, the preferred approach for integrity management by the DAF is damage tolerance (DT). The role of nondestructive inspection (NDI) is a critical component in DT as it provides periodic assessment to ensure no damage is present in the structure that exceeds the allowable size to remain in the desired level of risk for a structure. The definition of NDI in paragraph 3.22 of the MIL STD is “Nondestructive inspection 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. NDI generally refers to inspections that are conducted using equipment that is not part of or

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permanently affixed to the part being inspected. Inspections that do involve such equipment are generally referred to as in-situ NDI or structural health monitoring.” Therefore, SHM is defined as a subset of NDI and the definition for SHM is given in paragraph 3.35 as “structural health monitoring is a nondestructive inspection process or technique that uses in-situ sensing devices to detect damage.” For the remainder of this article, the term damage will be used as defined in MIL STD 1530Dc1 which is “damage to aircraft structure is any flaw, defect, crack, corrosion, disbond, delamination, discontinuity, or other type that degrades, or has the potential to degrade, the performance of the affected component. Damage can be inherent in the material, introduced during manufacturing, created during normal and abnormal operations and maintenance, or caused by material degradation.”

One important consideration for these definitions is that they do not address strain and loads monitoring in aircraft. These are governed by the usage monitoring of an aircraft and called Individual Aircraft Tracking (IAT). This includes the use of sensors such as strain gages or flight data recorders. The requirement in MIL STD 1530Dc1 is “all force aircraft shall have systems that record sufficient usage parameters that can be used to determine the damage growth rates throughout the aircraft structure and to determine other effects that impact service life such as overloads for composite structures.” Therefore, integrated sensing systems that monitor usage parameters are not considered to be SHM systems.

BACKGROUND

As MIL STD 1530Dc1 is a Department of Defense Standard Practice, processes and procedures defined in this document must be followed. As mentioned, the preferred approach used by the DAF to ensure integrity of aircraft structures is DT. The implication for NDI is given by the following sentence: “Criteria shall be established to ensure the aircraft structure can safely withstand undetected damage throughout its design service life.” Therefore, having a quantitative measurement of NDI capability to detect damage is required to realize a DT approach.

The method used for to determine NDI capability is described in MIL HDBK 1823A. “Nondestructive Evaluation System Reliability Assessment” [2]. The handbook provides the guidance for statistical analysis of NDI data to enable the determination of a Probability of Detection (POD) curve. It is this curve that is used in the calculation of acceptable risk and, thus, it is required for all techniques to detect damage in safety critical structures. A representation of the methodology used to calculate acceptable risk is shown in Figure 1. As shown, there are multiple parameters used for risk calculation and the NDI capability is one such critical parameter.

As SHM is a subset of NDI, a POD curve is required for the use of SHM on safety critical structures. For structures that are less critical, this requirement could be relaxed, but there needs to be a method to assess capability for each application.

There is a distinct separation in the use of in-situ sensors when applied to rotary wing aircraft. A common approach for helicopters and similar vehicles is health and usage monitoring systems (HUMS). In HUMS, sensors are typically used to monitor the rotating hardware required to keep the aircraft aloft. As these systems have substantial amounts of gears and rotating components, the sensors monitor the frequency of the system and provide a warning when there is a deviance from normal

frequencies of the acceptable operating state. This is a unique characteristic of rotary wing systems. This approach does not work well for fixed wing aircraft as the changes in resonant frequencies are quite small in the presence of a fatigue crack, especially when considering the structural complexity and variability found in fixed wing aircraft. As an example, the 22 factors that affect the ability to detect damage in a typical multiple-layered aircraft structures are shown in Figure 2.

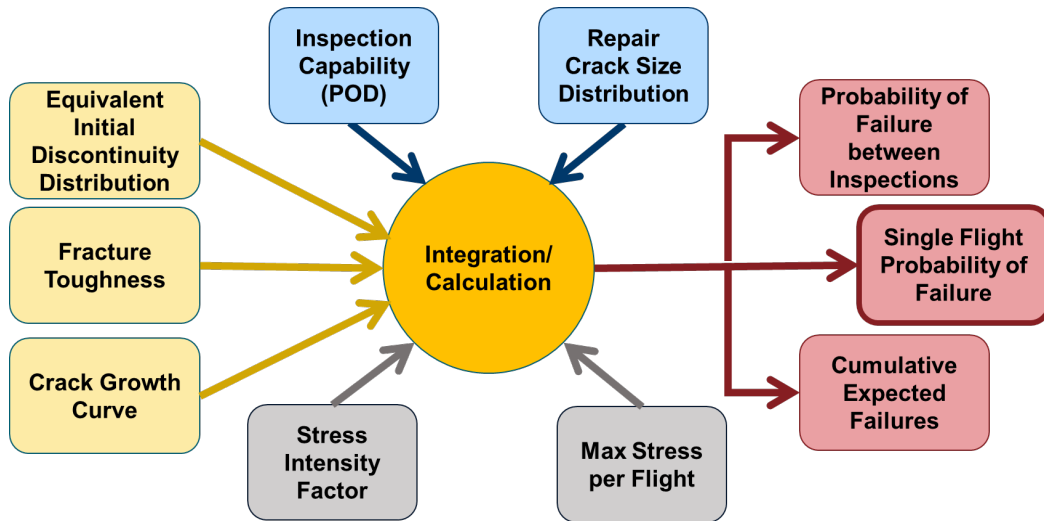


Figure 1. Representative damage tolerance risk assessment, in this case focused on fatigue in metal structure [3].

Example: Factors Affecting NDE of Two-layered Structure*

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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 (no. 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. Factors affecting NDI of a multi-layered structure [4].

The interrogation methods for SHM systems align with the methods used for NDI, namely mechanical waves, electromagnetics, and thermal diffusion. One additional sensing modality is the use of permanently installed mechanical sensors that provide a perturbation of a response when damage grows into the area covered by the sensor. Each approach has its benefits and drawbacks. For example, lower frequency electromagnetics is very effective at detecting surface breaking cracks in metal structure. However, very high frequency electromagnetics define ionizing radiation methods which are effective at detecting volumetric flaws, but is not very effective for planar damage, such as cracks or delaminations. Thermal diffusion techniques are effective in detecting planar damage in material with lower thermal conductivity, such as delaminations in polymer matrix composites.

For mechanical wave interrogation, multiple methods have been explored. Bulk wave ultrasound, such as longitudinal waves and angle-beam shear waves, are standard methods for detecting cracks and planar damage provided the ultrasound can be coupled to the region of interest. Another mechanical wave technique is acoustic emission (AE). However, AE is only present when damage is propagating and cannot be used to detect damage without active loading of a component. In addition, it is very difficult to discriminate a signal from damage growth from other mechanical signals which can lead to a substantial number of false calls [5].

A third method that has been extensively explored in the field of SHM research and development is guided wave ultrasound. This ultrasonic wave propagation mode is constrained by the geometry of the component in which it propagates, namely the thickness is such that the wave is a two-dimensional wave rather than a three-dimensional bulk wave. The cited benefit of using guided waves is their energy decay is inverse to the propagation distance, making them suitable for assessing large areas of plate-like geometry. However, a requirement for guided wave propagation is for the planar surfaces of the plate, not the edges, to be traction free for propagation. This means no additional material can be attached, such as stack-ups in multi-layered locations. Previous work has shown that when such stack-ups and constraints on boundary conditions are applied, the ability to detect damage is greatly impacted and sensitivity to small damage is lost [6].

Thus, many of the challenges in detection capability are similar for NDI and SHM, but the latter is made more challenging due to their permanent attachment to a structure. These challenges will be addressed in a subsequent section.

IMPLEMENTATION OPTIONS

Since the initial investment in SHM sensing capability in the late 1970's [7], significant focus has been on using these systems to replace current NDI procedures. The benefit is frequently cited as a reduced amount of time and aircraft preparation and restoration that are required to accomplish NDI assessments. This is based frequently on the incorrect perception that NDI techniques are performed as a function of time, not use of the aircraft. For the DAF, this requires the sensor to be integrated into the risk assessment method shown in Figure 1.

However, an alternative approach is being explored in civil aviation by Delta Tech Ops where the SHM system is used as a complementary technique to NDI processes [8]. In this specific application, a mechanical crack gage system is being used as a

maintenance guide for NDI. As the region of interest is hard to access, the SHM system provides redundant assessment capability that allows the inspection interval to be extended and provides multiple opportunities to determine if damage is present before it reaches a critical size. This approach is verified by a simplified POD assessment. It is not replacing the standard NDI procedure which is performed when the aircraft is inducted to heavy maintenance and region of interest is easily accessible.

A third approach that has been explored is to use the sensors as a trigger for an event driven maintenance action. This is much more common for composite structures where the ability to predict damage nucleation and growth remains a challenging problem [9]. As polymer matrix composites are certified for no allowed growth after initial impact below a certain magnitude, the use of NDI is event driven, such as after an impact. Having a sensing system that can accurately detect when such an impact occurs could be beneficial rather than relying on manual reporting processes.

Thus, there are multiple viable approaches for using in-situ damage sensing in aircraft and each approach needs to be evaluated for its capability and cost benefit as a function of the application. For the described possible use cases, significant technical hurdles remain for their eventual implementation.

REQUIREMENTS AND CHALLENGES FOR APPLICATIONS

The requirements when using SHM to address safety critical structure become significant. The Senior Leader for ASIP has provide three initial requirements, namely a POD curve, false call rate, and durability of the SHM system once install on DAF aircraft [10]. The technical effort to quantify these items is not trivial and additional decomposition of the application is required. Items to be identified include component geometry, material damage location and orientation, assembly (if applicable), and variability. As mentioned previously the variability includes the SHM system, the installation of the sensors, variability of the structure over the time the SHM system is to provide relevant information, and the nature of the damage. All these parameters are dynamic and will change over time. This makes meeting these requirements with quantifiable information extremely difficult. Currently there are no methods to ensure all these parameters can be addressed.

As a representative example, additional analysis can be performed for the three sources of variability: sensing system, structural variations, and damage variations. The list of variables that need to be addressed by the sensing system noted in Figure 2 are for an ultrasonic-based system, but similar variability can be applied to any type of NDI system. A critical characteristic for NDI systems is the ability to perform a detection sensitivity calibration before accomplishing an NDI procedure. This is unresolved challenge for SHM systems that rely on receiving a response from the material indicating the presence of damage. In addition, once a sensing system is permanently attached, changes in the structural configuration as a function of manufacturing, maintenance, repair, modification, and usage must be addressed to ensure reproducible detection capabilities in this extremely dynamic environment. Therefore, systems that rely on comparisons to previous measurements of the structure are challenged as the baseline is dynamic and changes for reasons that are not associated with damage. Algorithms that attempt to compensate for this change, such as regularization, must be fully validated to ensure changes being identified are unique to the presence of damage.

Another representative example can be found in damage variability. No two fatigue cracks are the same and frequently will have differing responses to any interrogation method. Previous work has illustrated that the same size fatigue crack can have as much as 20 percent variance the response from a standard eddy current probe [11]. Variations from ultrasonic signals can be even larger and can depend on the positioning of sensors. As an example, published work has illustrated that moving an ultrasonic sensor by 1 mm relative to an open fastener hole in a single layered structure change the detection capability for a guided wave-based system by over 100 percent [12]. These types of sensitivity variability need to be quantified if the output from an SHM system is to be used for risk management of safety critical components.

An alternative application of SHM uses the sensing system as a maintenance guide for additional actions. There are two potential scenarios for this approach. One is when the critical damage has multiple opportunities to interact with the SHM system, providing multiple opportunities to detect damage. The second approach is when the region of interest is not safety critical. The former situation is being explored extensively by commercial aviation as a cost-savings measure as mentioned in the earlier example at Delta Airlines. In this specific case, using SHM avoids the need for aircraft preparation and restoration required for NDI to be accomplished. Therefore, the aircraft is not in maintenance, but is in use and generating revenue for the airline. The latter scenario is more focused on possible military applications as the monitoring of non-critical regions could increase availability of aircraft to perform intended missions.

Regardless of the motivation for the potential to use SHM, there are common challenges to both. Previously mentioned factors included SHM system sensitivity calibration, confounding factors, and system capability performance demonstration. However, additional challenges exist for all potential use scenarios. These include the appropriate accelerated testing to ensure system durability and an understanding of possible sensing failure. The latter includes sensors and leads or cabling required for sensing, plus the SHM hardware, which can be placed on the aircraft or used as a plug-in measurement device. An additional considerations during failure is developing an understanding on how the performance of the system is affected by sensor failure as the potential for an immediate SHM system repair can be limited.

Another consideration is the installation of sensors onto an existing aircraft or their integration into a new design. For the former, there needs to be an analysis of optimized SHM sensor placement to meet the objectives of the sensing system while minimizing the weight and power requirements of the sensing system. Several approaches advocate for integrating SHM sensors into the material being used which leads to the requirement to assess how the sensors affect material performance. This could require additional certification testing which adds to the development effort for the new aircraft.

Thus, the technical challenges are not trivial. Assuming all the technical benefits of an SHM system are realized, there remains a need to perform a cost benefit analysis to determine if the use of an SHM system is a viable option for the intended application. Cost factors that need to be included are the up front development costs, the certification process costs, and the support costs once the SHM system is implemented. It is important to recognize the business case being pursued by commercial aviation are significantly different from those that apply to military aviation.

CURRENT EFFORTS

As mentioned previously, the first funded efforts to develop an SHM system occurred in the late 1970's and was focused on acoustic emission [4]. Initial attempts to implement this capability suffered from extensive false calls and caused excessive unnecessary maintenance [13]. This caused a pause in investments for this capability, followed by a re-invigoration in the early 2000's. Unfortunately, progress has been slow in the development of capability and much of the work has been focused on academic research projects. A common theme in this work is the development of new sensing systems, new damage detection algorithms, and novel techniques for sensor integration. Much of this work is centered on canonical structural configurations, typically a flat plate with sensors on the perimeter detecting damage in the center of the plate as shown in Figure 3.

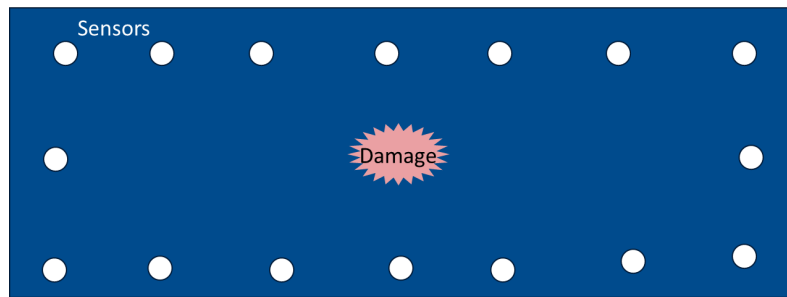


Figure 3. Representative flat plate with sensor configuration pursued in many academic research efforts.

While this structural configuration can be used for initial exploration with the justification that it is representative of a wing skin, the reality of military aviation is that an inspection of a large area such as a wing is an exception and not representative of a typical inspection requirement. A more representative depiction of a typical military inspection scenario is shown in Figure 4 [14]. This illustrates multi-layered nature of joints in aircraft. Stresses are focused predominantly on specific areas in the joint, namely at faying surface between layers. Therefore, this is the typical location for fatigue cracks to nucleate and grow at these stress concentration locations. Depending on how the aircraft is assembled, there could be sealant between the layers which can facilitate coupling of ultrasound from one layer to the next, but this situation is very application dependent and needs to be verified for each aircraft.

Due to the complexity and localized variability in these types of structures, addressing all the concerns listed in the previous section using only empirical methods is a major endeavor. Previous effort, such as the US Navy Integrated Hybrid Structural Management System (IHSMS) [15], illustrated these difficulties. This multi-million-dollar effort used empirical assessments on various test articles in attempts to establish capabilities for multiple SHM and IAT sensing systems. However, due to the limitations of time and resources, not all the factors listed above could be evaluated. Therefore, while the program was successful in exercising multiple assessment methods, the data was not sufficient to establish sensitivity values for all possible anticipated Navy structural components.

To overcome this limitation, various simulation capabilities are being explored. As an example, the Federal Aviation Administration (FAA) Technical Center is coordinating an all-volunteer group within the commercial aviation community to use

simulation tools to explore the potential of using models to help evaluate the sensitivity of SHM systems. This has been a long-term effort within the NDI community and is called Model-Assisted Probability of Detection (MAPOD) [16]. The MAPOD initiatives seek to minimize the use of empirical data to validate the capability, i.e. reproducible sensitivity, of the interrogation method to detect the damage features of interest. For the FAA coordinated project, team members include representatives from OEM aircraft manufactures, commercial airlines, and providers of SHM equipment. The scope of this effort is to demonstrate the potential to use simulations to facilitate the capability evaluation for a representative inspection requirement. The structural element and interrogation methods were selected by consensus and represent a two-layer butt joint interrogated by a guided wave ultrasonic approach. Specific requirements for detection have not yet been established, though the geometry is intended to represent a simplified fuselage joint. The simulation tools for this application are in development by several differing commercial and academic entities.

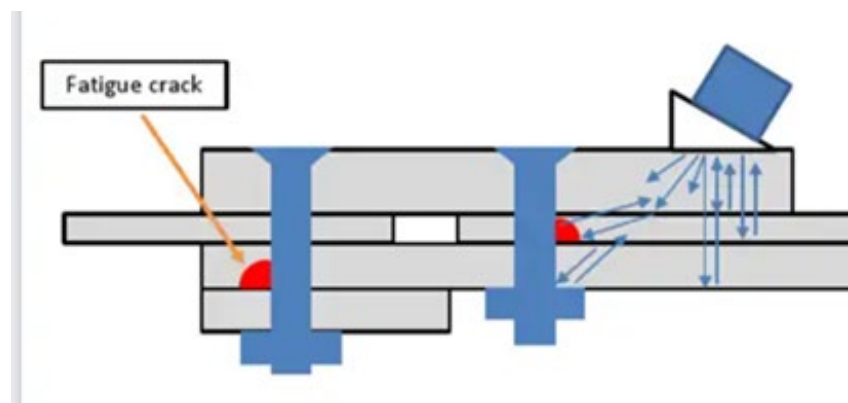


Figure 4. Representative depiction of a typical military inspection scenario [14].

One consideration for simulation-based approaches is the need to validate any models being used, especially for safety critical applications. Therefore, the simulation tools need to include methods to vary the parameters that will affect sensitivity. As part of general practice for a POD assessment, all potential factors that could affect the interrogation response need to be evaluated to determine if they have meaningful impact on the sensitivity of the SHM system. For those that are found to affect the sensitivity of the response need to be included in a comprehensive validation study that typically includes benchmarking the model response when compared to well-controlled experimental data.

Additional work has been explored to address confounding factors such as uniform temperature changes [17] and tensile strain fields [18]. However, the degree of complexity in these factors has not been fully evaluated, such as the effect of a dynamically changing three-dimension strain field that includes tensile, bending, and torsional strains, or temperature gradients across the region of interest. These types of variations are present in typical measurement environments and need to be addressed in future evaluations.

POSSIBLE WAY FORWARD

The challenges to realize effective SHM cannot be trivialized. Considering all the factors that can affect potential sensing modalities, an empirical test process would take significant time and resources, plus would have to be tailored for each application. Therefore, a suggested way forward would include a hybrid of both empirical testing and simulations to obtain resolution on how these multiple factors affect the response from the SHM system. With this approach, the parameters that could impact the SHM technology can be decomposed to apply a rigorous engineering-based approach to systematically determine the magnitude of the impact for each factor. Once this is established, multiple parameters can be integrated to determine if they assist or hinder the ability of the SHM system to detect critical damage.

Another consideration that could accelerate the implementation of SHM is to develop an approach that is complementary with current NDI processes, especially if this is initially applied to non-safety critical structures. For these locations, it is possible that some of the more stringent requirements that have been put forth could be relaxed and provide a venue for initial long-term durability assessment when coupled with other accelerated test techniques. The application of SHM to these locations could enable early detection of damage in non-critical locations, enabling simplified and lower cost repairs and returning aircraft to service faster than what can be achieved with current processes.

SUMMARY

This overview has attempted to summarize approximately 40 years of significant investment in the development of SHM capability and highlights the challenges that need to be addressed for its eventual implementation. An expansive literature base exists that illustrates the potential of various SHM modalities. Initial efforts to implement SHM on fixed wing DAF aircraft was not successful and led to multiple false calls and some disillusion with this capability. One aspect with the initial efforts was they did not fully integrate the derived requirements that come with the DAF ASIP DT approach as specified in MIL STD 1530Dc1. This includes requirements for a POD curve when addressing safety critical structure. Generation of POD curves and addressing additional attributes, such as false calls and system durability, are substantial technical development efforts. This is especially true if empirical approaches are used to generate the required test data to address all possible operational and environmental factors that could affect the capability of an SHM system and impact its ability to reproducibly detect damage.

Two primary implementation options can define the way forward for SHM. One is to for safety critical structural applications, while the other addresses non-critical structure that has become a maintenance burden. The latter application could relax some of the requirements for implementation, but both applications would benefit from an approach that uses complementary NDI to ensure the objectives of the inspection requirement are being met. To satisfy the multiple requirements for implementation, a strategy that combines simulation and empirical testing is recommended. Relying exclusively on empirical approaches is anticipated to take significant time and resources relative to the benefit of using SHM. This includes a rigorous engineering-based

approach to systematically address the effect of relevant factors that could affect the reproducible capability to detect damage for each intended SHM application. When properly executed, the recommended approach could enable SHM to realize its potential to increase aircraft availability while reducing the overall maintenance burden currently in place to ensure aircraft integrity.

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