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USAF Perspective on Foundational Challenges for Enhanced Damage Sensing

E. A. LINDGREN and D. STARGEL

ABSTRACT

Structural integrity programs of the United States Air Force (USAF) include periodic inspection to detect damage before it grows to a critical size that can impact the safety of USAF systems. Current inspection methods have been used successfully to ensure the required risk metrics for these systems are being met as mandated by the relevant USAF Standards. However, there is a continual desire to improve the capability of inspection methods while increasing the efficiency and reliability of these methods. As new approaches are being explored for the enhancement of damage sensing, a number of foundational issues that represent hurdles for the application of these enhancements have been identified. This paper provides background of how damage sensing is used by the USAF and expands on identified foundational challenges that represent technical barriers to the implementation of new damage sensing methods. As the desired capability of the damage sensing methods expand from detection of damage to the characterization of damage, the degree of complexity grows and additional challenges emerge. Representative case studies are used to illustrate challenges for detection, localization and characterization of damage.

INTRODUCTION

The requirements for the methods to ensure the integrity of US Air Force (USAF) structures are governed by MIL-STD-1530C. The management of the integrity of aircraft structures is led by the Aircraft Structural Integrity Program (ASIP) with individuals responsible for each weapons system. Due to previous experience in aircraft structures, the USAF uses a damage tolerance approach to ensure integrity. The successful application of damage tolerance to meet the metrics for structural risk is highlighted in the annual ASIP Conference. A critical piece of information presented is that the USAF is currently meeting its safety metrics with respect to structural integrity. Another important item to recall is that the US Navy, US Army,

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Eric A. Lindgren, Materials and Manufacturing Directorate, David Stargel, Air Force Office of Scientific Research, Air Force Research Laboratories, Wright-Patterson AFB, OH and Arlington, VA

and civil aviation do not necessarily use the same approach to ensure structural integrity.

Damage tolerance is used for the management of slow fatigue crack growth as there are methods for predicting the rate of crack growth. Thus, inspection can be performed at regular intervals that are determined as a function of the inspection capability, the critical size of the crack before possible failure, and the rate of crack growth at a specific location. Note that this is only one of many data inputs into the determination of the risk of structural failure. In addition, to enable the calculation, the entire probability of detection (POD) curve must be available for the ASIP Managers. For other types of damage, such as corrosion in metals, and other types of materials, such as polymer matrix composite, there is no available and validated approach for predicting the rate of damage progression. Therefore, when this type of damage is found, sometimes occurring because of an event, the requirement is to repair the structure to within acceptable repair criteria, or replace the part in question.

As noted above, the risk calculation for fatigue cracks requires the entire POD curve for the inspection process. For this paper, this will be referred to as validated capability, which has to be determined in a relevant environment (i.e. testing of real structures) and would be considered equal to a Technology Readiness Level (TRL) of 6. Laboratory testing on coupons/components will be defined as verification and has a TRL of 4. The challenge for categorizing the maturity of technology is when flight tests are performed. While a demonstration in an operational environment is commonly considered to have a TRL of 7, if the capability has not been validated, it still remains below a TRL of 6.

DAMAGE SENSING CAPABILITES / REQUIREMENTS

As USAF aircraft age, there is the potential for increased inspections. Typically this does not mean additional recurring inspections at the same location as the capability of common inspection methods are defined for USAF applications [1] and this capability that sets inspection intervals. Recent presentations have highlighted how improved capability can greatly extend inspection intervals [2]. However, extended use beyond original design life, evolving missions, and new engineering analysis can identify additional locations that require inspections. A challenge with these locations is they can be remote, hidden, or otherwise require extensive maintenance actions to enable inspections to be accomplished. This has led to research to enable permanent placement of damage sensing systems in aircraft to reduce disassembly and other maintenance actions to enable inspections. Thus, the challenge for deployment of new damage sensing methods is the need to satisfy two entities within the USAF; one is ASIP that needs to ensure safety and the other in the maintenance organization that needs to minimize the time and cost to perform the work that ensures safety. As an observation, these two needs are not always symbiotic.

To meet the need for damage sensing, typically three types of sensing physics are used. The first is stress wave propagation, including vibration analysis in Hz frequency ranges up to acoustic microscopy performed in GHz regimes. This includes all ultrasonic methods, such as longitudinal, shear, Lamb, shear horizontal, extensional, acoustic emission, and other specialized and higher order guided modes. Note that these methods can require an active interrogation, or passively detection, such as with acoustic emission. The second is electromagnetics, which includes frequencies from low Hz to the upper limits of ionizing radiation. This includes methods such as eddy current, THz, IR and x-rays. The third is thermal diffusion, used for materials with relatively low thermal diffusivity, e.g. composites. In addition, some damage sensing uses mechanical devices, such as crack gages and related devices, requiring damage to run through the sensor to be detected. Finally, there are specialized techniques that combine different sensing modalities, such as sonic infrared, or use mechanical excitation to image damage, such as shearography.

One very important feature of the damage sensing methods is that all modalities can be applied either via temporary contact of the sensing device, such as a transducer, or a permanently attached *in-situ* sensor, such as a piezoelectric disk. Therefore, regardless of how the sensor is placed in contact with a structure, the sensing modality interaction is the same, which means the two approaches are very closely related. The difference has become one of nomenclature and the challenges for reliable sensing of damage with statistical performance are very similar regardless of the approach. Neither approach is new, with damage sensing systems being developed within the USAF since the 1930s [3] and concepts for permanently attached sensors being researched in the early 1980s [4] and flown on a fleet of USAF aircraft in the mid to late 1980s [5]. However, even after many years of research and development of technology for new materials and damage types, there remains significant challenges at the foundational level that need to be addressed before damage sensing can meet the desire to have statistically validated capability for aerospace applications that minimize the need for extensive maintenance actions.

AEROSPACE STRUCTURAL DAMAGE SENSING: COMPLEXITY

It is important to note that the following discussion addresses only methods to detect, localize, and characterize damage and does not address other system parameter monitoring, such as those recorded by strain gages and accelerometers. Research and development has been active for many years to realize damage sensing with different degrees of success, especially in the domain of characterization. The reality is this often becomes very difficult as the structural conditions on assembled aircraft are much different for simulated structure used in laboratory environments. The primary difference is the variability found in aircraft, especially some of the older aircraft that are still in use within the USAF.

Sources of variability come from design, manufacture, modification, repair, maintenance and even flight-to-flight changes due to usage. While changes in design can be readily accommodated, the other five factors can change stochastically from one aircraft to another, even in the same model series. As regions of interest for inspection development typically reside in buried, complex structure with multiple joints and fasteners, even small changes in the stress state due to a flight load spectra can change the interaction of a sensing modality, such as an ultrasonic wave, with the structure in question. Consider the simple two-layer joint joined by a fastener, such as the joint shown in Figure 1. For the sensing of damage in this location, twenty-two factors can be identified that affect the reproducibility of the results [6]. These can be broadly classified as being dependent on the sensing method, the condition and geometry of the part in question, and the characteristics of the damage to be detected.

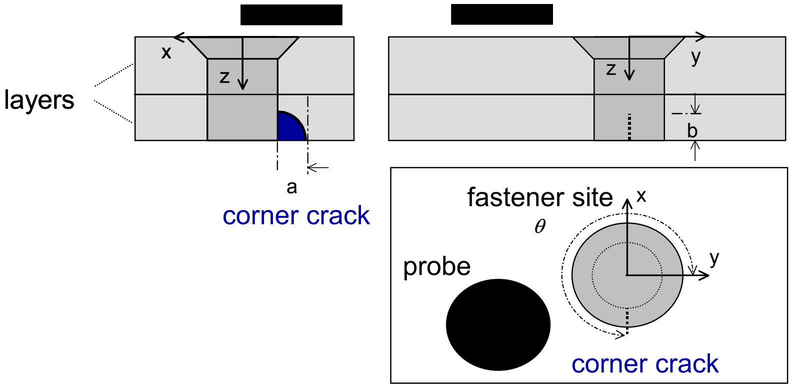

Figure 1. Representative fastened two-layer structure with damage at fastener.

To provide even greater specifics on the variability, consider the interaction of a damage sensing stress wave interacting with the fastener hole. The reflection of the signal from the hole will depend on the condition and nature of the fastener-to-metal layer boundary, the geometry of the hole, the fastener type and condition, presence and uniformity of sealant, presence and proximity of other structural features, and the risk of multiple damage types (e.g. fatigue crack and corrosion). All these parameters have been found to vary in real aircraft structure and can affect the validated capability of any damage sensing method. Similar issues arise when assessing structure made from other materials, such as polymer-matrix composites.

The feature shown in Figure 1 is greatly simplified when compared to what is commonly found in real aircraft. Figure 2 illustrates a representative cross section of structure that consists of 5 layers, three different materials, and multiple spacing between the fasteners [7]. The specific figure shows an ultrasonic probe for the inspection on one of the middle layers for cracks away from the fastener in which the sensor was inserted. Due to the nature of the structure, there was no location for the placement of the sensor on the layer of interest. In addition, non-uniformity existed in the boundary conditions between each layer and within the boundary between two specific layers, leading to issues of reproducibility for this inspection. Related complexity can be found for structures with vertical risers with fastener holes that require damage sensing for cracks emanating from the hole and /or from edges and radii in such classes of structure [8]. To address these sources of complexity requires an in-depth assessment of the factors that affect the ability to reliably sense damage.

Figure 2. Representative complex multi-layered aerospace structure [7].

AEROSPACE STRUCTURAL DAMAGE SENSING: CHALLENGES

When addressing these classes of complex structures, it is tempting to start by deconstructing the problem as a function of the variables for the specific application. However, approaches are required that are not exclusively application dependent, but agnostic to address all domains of complexity and variability. Therefore, a significant and difficult challenge is to develop methods to address multi-parameter variability where the sources of variability include the sensing methodology, the condition and complexity of the structure in which the sensing will occur, and nature of the damage to be detected. For permanently attached damage sensing systems, the time variance of these variables needs to be considered to ensure reproducible capability to sense damage for the life of the sensing system. In addition, external factors of the environment and operating conditions of the structure need to considered. Thus, the effects of competing factors, both constructive and destructive, need to be balanced and addressed to ensure the capability to sense damage is not compromised.

Variance in a number of the factors mentioned in the previous paragraph could be addressed by complementary measurements and/or other compensation methods. However, when variance becomes stochastic and is not regular and/or periodic, validated damage sensing capability becomes even more challenging. An example of this variability can be found in the use of guided ultrasonic waves to detect damage. Research to develop this damage sensing technique has been reported for many decades [9]. However, for this technical approach to address more than single layered structure, the stochastic variance in the boundary conditions of a multi-layered structure, which is present in typical aerospace applications, and its effect on the damage sensing capability must be addressed. Examples have been presented where simple changes in boundary conditions can dramatically change the sensitivity to damage detection [10]. This does not mean that this approach is not viable, but to obtain a validated capability the variance in sensitivity is a foundational issue that must be resolved.

Another parameter considered is the influence of factors that are present at different length scales. For example, factors discussed in the previous paragraphs are predominantly at a macro-scale and are relevant for features at the macro-scale level. However, projected increase use of materials with tailored microstructure requires that the damage sensing methods address features at this level as well, even when the damage refers to microstructural perturbations and not the presence of a macro-scale feature, such as a fatigue crack. This requires a detailed knowledge of how the microstructure can affect damage sensing capability and develop approaches to integrate this affect in the technique to determine if damage is present. In addition, it requires the overlay of the macro-scale features and how they can influence the sensitivity to damage at micro-scale levels.

The large number of factors that can cause variance means that the assessment of the effects of variance could require an extremely, if not outright unrealistic, large sample set to determine how the factors confound each other. For this reason, it is anticipated that modeling will play an increasing significant role in future research in the domain of damage sensing. A rapid scan of previous proceedings of conferences addressing damage sensing indicates such an increased focus on modeling is already occurring. However, a limitation in current modeling efforts is the reliance of case specific modeling, such as numerical methods and variants of this approach. New modeling approaches are needed to provide efficient and effective solutions to enable simulation of all parameters that can change sensitivity and evaluate the capability to sense damage. The modeling should address adaptability to changes in variance and the stochastic nature of the variance. Realization of this capability, which is also a non-trivial problem and has a high degree of complexity, could be a critical aspect in accelerating the potential transition of new damage sensing methods as model-assisted validation methods [11] can provide the end-user of the damage sensing system with the critical parameters required to manage the integrity of structural components.

A critical factor in the use of modeling is the validation of the models. If damage sensing methods are to be developed and their capability validated with the assistance of models, then the criticality of validating the models increases. As the number of factors integrated in the modeling increases, the ability to develop new approaches for validation becomes essential so the validation process can be expedited. This challenge is not unique to the domain of damage sensing, but the number of stochastic confounding factors that need to be integrated into the modeling process present additional issues that have to be addressed in the development of improvements in the model-assisted validation techniques.

One concern as new damage sensing methods are developed is the interaction of all the information available to the individual making the final disposition any indications of damage. Multiple research efforts, too many to cite, have developed various degrees of automation to assist in the determination of the presence of damage. However, the decision making processes are commonly based on comparisons and/or relative assessments. For implementation into maintenance and integrity management processes, the determination will have to be more absolute and could require final interaction with decision making that integrate much more data than what is available from just the damage sensing system. Therefore, automation of analysis of all relevant data and presenting this in a comprehensive fashion that simplifies, but over-simplifies, the decision making process.

The above challenges need to be considered from all aspects of damage sensing. Detection is a one-dimensional problem, either damage of a specific size or larger is present or it is not. Adding the desired attributes of locating and characterizing damage adds six more dimensions to the problem and has occupied the research community for many years. The challenge for approaches to characterize damage is the transition from diagnostic approaches with multiple data inputs to one that is more an inversion of all available data. This needs to be coupled to statistical methods to address the ill-posed nature of the inversion as there are many more factors affecting the capability to characterize damage than there are data points to address all of the confounding factors. Characterization techniques must evolve into more diagnostic methods and migrate away from demonstrations in idealized conditions. This includes the integration of the complexity and variance into the inversion algorithms. The outputs of such inversion techniques need to provide metrics that are relevant to both maintainers and structural engineers for their respective needs in the use of damage sensing systems. This is especially important for the realization of Condition-based Maintenance, as the condition of the system will determine the course of action for ensuring both the risk of failure and the cost of maintenance are minimized. Thus, the multi-dimensional solution will require statistical metrics for every dimension if it is to be used for managing the risk and maintenance process of USAF aircraft.

AEROSPACE STRUCTURAL DAMAGE SENSING: SUMMARY

The objective of this paper is to highlight the foundational research and development challenges that exist for reliable and robust damage sensing. In summary, foundational research is required to address the stochastic, unstable, multi-faceted, and varying sensing environments found in typical aerospace applications, but are believed to be relevant in other applications. Resolution of these foundational issues will enable the development of applied solutions for these applications. There is no intent to provide a prescriptive solution to these challenges, but it is worth considering the role of modeling and the use of Bayesian approaches, both with and without *a priori* information, as potential solutions are developed and discussed. The technical developments of approaches and methods to address these challenges are important factors for implementing new techniques to ensure safe, capable and, available aircraft for the USAF.

REFERENCES (the ones in italics need additional information)

1. Structures Bulletin “Nondestructive Inspection Capability Guidelines for United States Air Force Aircraft Structures,” EN-SB-08-012, Rev B.
2. K. Jones, B. Harris, J. Killian, B. Lewis, and K. Kennedy, “The F-16 Quest for NDI Capability Guidelines Compliance,” Aircraft Airworthiness and Sustainment Conference, 2012.
3. Materials Laboratory Historical Report, 1 January - 30 June, 1953, AFRL/ML Data Base 1003, located at Universal Technology Corporation.
4. P.H. Hutton and D.K. Lemon, “Development of Acoustic Emission Methods for In-flight Monitoring of Aircraft Structures: Review of Progress in QNDE, Vol 2A, p459 (1983).
5. C. Bakse, Airlift Tanker: History of U.S. Airlift and Tanker Forces, Turner Publishing, 1996, p63.
6. E.A. Lindgren, J.S. Knopp, J.C. Aldrin, G.J. Steffes, and C.F. Buynak, 2007. “Aging Aircraft NDE: Challenges and Opportunities,” Review of Progress in QNDE, Vol 26B, p1731 (2007).
7. J. Hoffmann, J. Ullet, B. Drennen, “Development of a Nondestructive Inspection (NDI) Approach based on Bolt Hole Ultrasonic Testing (BHUT) for Complex, Multi-layered Aircraft Structures” Aircraft Structural Integrity Program Conference , 2007.
8. E.A. Lindgren, et. al. “Probability of Detection Results and Deployment of the Inspection of the Vertical Leg of the C-130 Center Wing Beam Spar Cap,” Aging Aircraft Conference, 2005.
9. B.A. Auld, “New Methods of Detection and Classification of Surface Flaws,” Proc. ARPA/AFML Review of Progress in QNDE, AFML-TR-78-55, p108 (1978).
10. E.A. Lindgren, J.C. Aldrin, K.V. Jata, B. Scholes, and J.S. Knopp, 2007. “Ultrasonic Plate Waves for Fatigue Crack Detection in Multi-layered Metallic Structures,” Proceedings of Health Monitoring of Structural and Biological Systems, SPIE Vol. 6532, 1: 1-14.
11. E.A. Lindgren, E.A. Medina, J.C. Aldrin, and C.F. Buynak, “Demonstrating Capability Validation Protocol for in-situ Damage Detection,” Aircraft Structural Integrity Program Conference, 2011.