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AGING AIRCRAFT NDE: CAPABILITIES, CHALLENGES, AND OPPORTUNITIES (PREPRINT)

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U.S. Air Force aircraft are managed by Damage Tolerance Assessment (DTA) and Nondestructive Evaluation (NDE) plays a critical role in insuring their flight safety. This paper provides an overview of current NDE capabilities for aircraft structures. The potential migration to Condition-Based Maintenance (CBM) will require NDE to evolve from detection of defects to characterization of their location and size. This represents multiple significant challenges as aircraft have many material and geometry factors that complicate this analysis. This paper provides a strategy to resolve these factors.

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ABSTRACT. US Air Force aircraft are managed by Damage Tolerance Assessment (DTA) and Nondestructive Evaluation (NDE) plays a critical role in insuring their flight safety. This paper provides an overview of current NDE capabilities for aircraft structures. The potential migration to Condition-Based Maintenance (CBM) will require NDE to evolve from detection of defects to characterization of their location and size. This represents multiple significant challenges as aircraft have many material and geometry factors that complicate this analysis. This paper provides a strategy to resolve these factors.

Keywords: Aging Aircraft, Damage Detection, Damage Characterization, Multi-layered Structure, Vertical Stiffener Structures
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INTRODUCTION

The average fleet-wide age of US Air Force aircraft continues to increase [1]. Existing aircraft are being used for longer service lives or more damaging operations than were anticipated during the design and development of the aircraft structure. As a result, there is an increased emphasis on the maintenance of US Air Force aircraft. The Aircraft Structural Integrity Program (ASIP) develops the strategy and sustains the processes used to maintain the aircraft for each Mission Design Series (MDS).

Across the aerospace industry several strategies exist to manage the structural integrity of aircraft, which are Safe-Life, Damage Tolerance Assessment (DTA), and Conditioned-based Maintenance (CBM). Currently, the US Air Force uses DTA. In very simplified terms, the DTA approach assumes there are very small flaws in an aircraft that cannot be detected by NDE. The aircraft will be flown until crack growth models estimate that there is a small probability that a crack has grown to a size above what is detectable by NDE, but remains smaller than the critical flaw size for the structure. If no flaws are detected in maintenance procedures, the aircraft is returned to service and the crack growth models are reset to indicate that there are no cracks present that are larger than the minimum detectable crack size. Thus, the aircraft can be flown until the crack growth models indicate that the there is a small risk a crack has formed that exceeds the limits of detection, but is not larger than the critical crack size. This strategy requires reliable NDE techniques to inspect the aircraft. It is important to note that this approach only requires the detection of flaws.

A new strategy for managing aircraft, called CBM, will require the detection and characterization of flaws in aircraft. With this approach, maintenance on an aircraft structure will be performed only when the flaw is approaching the critical flaw size. Thus, this method requires determining the location, orientation, and size of the flaw. For example, an indication of a fatigue crack by a fastener in a multi-layered structure will require determining the layer at which the crack is located, the direction the crack is oriented away from the fastener hole, the length of the crack and if there is more than one crack present at the fastener hole. This is significantly more information than what is required using DTA. Thus, the objective of this paper is to review current capabilities in aerospace structures NDE, present technical hurdles that hinder current NDE techniques from characterizing flaws, and a strategy to overcome these obstacles to enable flaw characterization, as required for the deployment of CBM.

CURRENT CAPABILITIES

The use of CBM will require the development of additional techniques to analyze and extract information from NDE data. It is very important to note that current NDE inspection techniques do not routinely determine the size, location and orientation of damage in aircraft structures. Exceptions exist, such as some types of bilt-hole eddy current, but they typically require significant disassembly of the structure/component to enable the flaw characterization. While some of this capability may exist in other industries when inspecting very simple structures, such as pipes, aircraft structure has many additional complicating factors that prevent this type of analysis with current inspection techniques. These complicating factors will be reviewed in a latter section of this paper.

To address current capability, it is possible to divide an estimated 80 percent of aircraft structure into two categories: multi-layered structures and vertical stiffeners. Multi-layered structures include many surfaces and/or complex geometry items joined over large broad areas. Vertical stiffeners provide structural reinforcement to large areas and can include fastener holes to attach other internal structures. This section will review current capabilities to detect fatigue cracks in these two classes of structures.

Multi-layered Structures

Multi-layered structures are defined as two or more layers of material that overlap, typically to join two or more structures together. Joints that include three or more layers are not uncommon. In addition, the layers can be of multiple types of materials, can include the presence of sealant, and may include various shims between the layers. The potential complexity of these parts is shown in Figure 1, which requires the detection of fatigue cracks in the fourth of eight layers. These layers do not have sealant between them and three layers are shims, in which flaws frequently occur but do not affect the structural integrity of the part and should not be reported as damage during an inspection.

Typically, these types of structures are inspected using either eddy current or ultrasonic techniques. The ability of these two inspection methods to detect fatigue cracks can be classified by where the inspection is performed, i.e. whether the work is being done in a

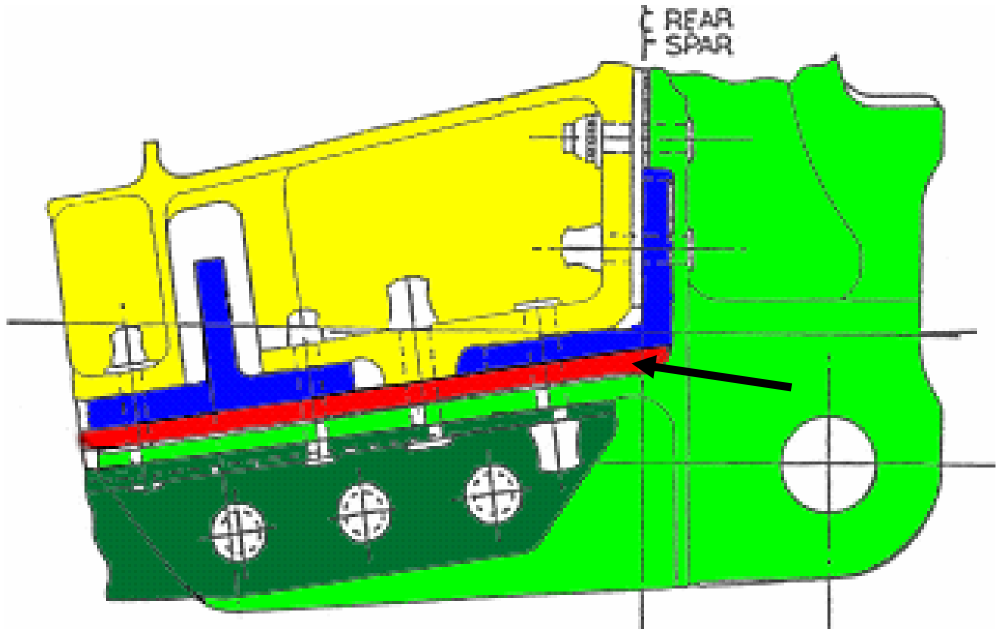

FIGURE 1. Representative multi-layer aircraft structure requiring detection of fatigue cracks in the layer indicated by the arrow.

field environment, in a Depot maintenance facility, or in a laboratory. The sensitivity of eddy current techniques when inspecting this type of structure is determined by the frequency of operation and the type of metal being inspected. In a field or Depot environment, this method is used to detect surface breaking cracks. In the laboratory under more exacting conditions, it is possible to detect subsurface fatigue cracks. However, recent probability of detection (POD) studies indicate the maximum capability for eddy current techniques to detect far surface flaws, i.e. fatigue cracks located on the opposite surface from the location of the eddy current probe, is cracks equal to or greater in length than the total thickness of the structure being inspected [2].

To use ultrasound for the inspection of a multi-layered structure requires the presence of couplant between the layers. Sealant functions as a couplant for the ultrasonic energy to propagate from one layer to the next [3]. When this condition exists, laboratory work has shown that very small defects, 0.025" electric discharge machined (EDM) notches, can be detected at 90/95 POD sensitivity for thickness values up to 0.5" [4]. Thicker structures can be inspected provided the ultrasonic energy can reach the location of a defect and detection of flaws as small as 0.080 EDM notches has been reported for structures over 2.0" thick [5]. In depot environments, this approach was used for detecting second layer fatigue cracks in structures up to 0.5" thick with a demonstrated 90 percent POD sensitivity of 0.073". When ultrasonic techniques are used in the field environment, they are typically used only for detecting fatigue cracks in the far surface of a single layer that are perpendicular to that surface for components that are too thick for conventional eddy current techniques. For these requirements, typical sensitivity to fatigue cracks is cited as 0.100" [6]. However, these inspections require precise manual manipulation of the transducer and use portable inspection equipment. Recent evidence indicates that the reliable sensitivity of these manual inspections is not as expected [6].

Vertical Stiffeners

Vertical stiffeners are integrated structural components of large areas of relatively thin metal, such as that found in wing and fuselage skins. A representative structure is shown in Figure 2. The vertical riser is typically not thicker than 0.5" and usually has holes, as indicated by the cross-hatched region, from which fatigue cracks can emanate, as shown by the solid regions above and below the hole. For some areas, this hole enables liquid to transfer from one area to an adjacent area. When there are no fasteners and there is access to these holes, bolt-hole eddy current techniques are typically used for inspecting these holes. However, it is more common to have these holes used as attach points for internal structure of the aircraft, requiring fasteners to be placed in the holes. The presence of fasteners, combined with other internal structure, can prevent access to the fastener holes, which requires an inspection technique that works with access to only the exterior of the area with the vertical stiffener.

Typically, an ultrasonic inspection technique would be developed for this type of structure. It is based on using creeping waves, which mode convert from a shear wave at the fastener wall and propagate around the exterior of the hole [7]. The sensitivity of this technique has been augmented by using software-based automated analysis routines to aid the inspector in interpreting the ultrasonic data, which can include geometric reflections and superimposed signals [8]. A recent success story transitioned this approach to a production-based technique to inspect the vertical leg of the lower spar cap. This structure included two fastener holes, one above the other, and has only a small area available for the placement of the ultrasonic transducer, as shown in Figure 3. The vertical component of this structure is tilted an additional 10 to 20 degrees from the accessible surface of the aircraft, which requires a special compound angle transducer to enable the generation and detection of the ultrasonic waves. The automated data analysis software was required to address interfering reflections from the side walls and inside the fasteners, which allowed the complex signals from this inspection to be analyzed in a reasonable timeframe relative to the time to collect the data from this structure [9].

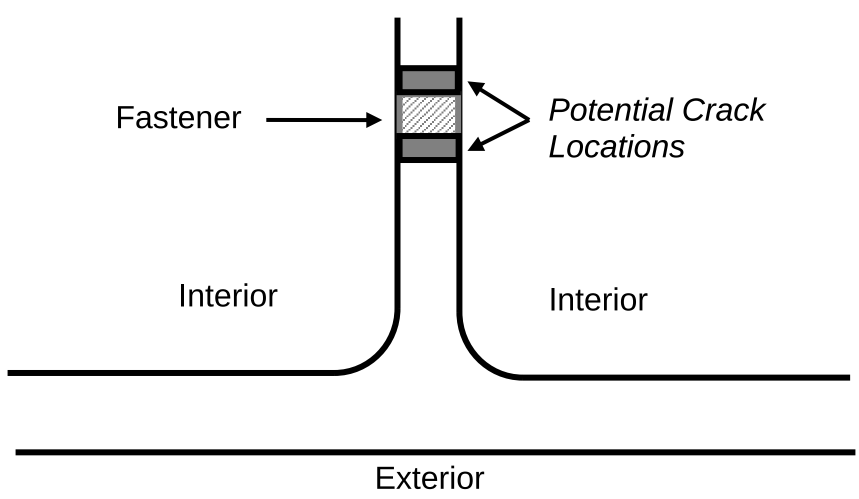

FIGURE 2. Representative vertical stiffener structure requiring detection of fatigue cracks indicated by the shaded region above and below the fastener hole.

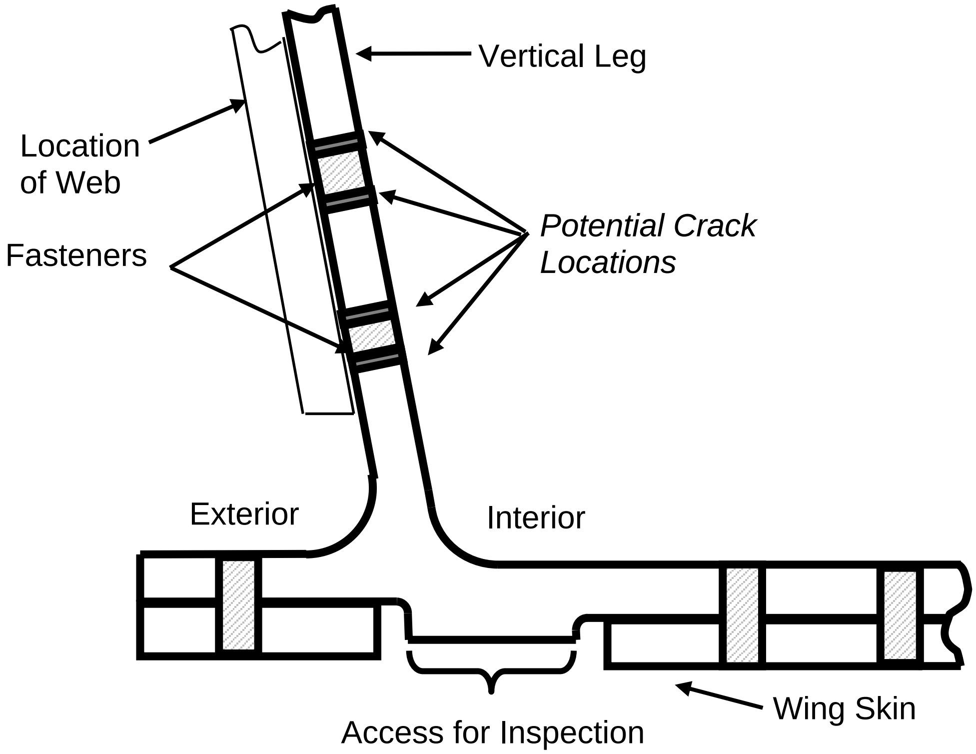

FIGURE 3. Side view of the lower spar cap structure showing the limited access and the location of the potential fatigue cracks that must be detected by this inspection.

The ultrasonic approach was validated by a POD study, which indicated the technique can detect 0.100" EDM notches at 90/95 [9]. The equipment required for this inspection dictates that it be used predominantly as a Depot-based inspection by highly skilled inspectors. However, there are currently contractor field teams deployed for this specific inspection. In a laboratory environment, it is possible to obtain an improved sensitivity to smaller flaws. However, the ultimate factors that limits this sensitivity is the frequency of the creeping wave and the magnitude of the noise from additional scatter of the ultrasonic energy in the structure.

Unfortunately, this type of structure does not lend itself to eddy current inspection, as the distance from the accessible surface to the fastener hole is typically more than 0.5", which would require low frequency signals for the eddy current to penetrate to the fastener hole. At these low frequencies, the sensitivity of the eddy current technique to smaller flaws is not good, plus geometric features of these types of structures, which include the curved surfaces at the base of the vertical stiffener, can generate signals that are significantly larger than the signal expected from a defect. Thus, eddy current techniques are only used in the field and Depot environment with production-based equipment to detect fatigue cracks as they approach the accessible surface and can typically detect the cracks when they are within 0.125" of becoming a surface breaking crack. In the laboratory, the size of flaw that can be detected will vary as a function of the geometry and frequency used for the inspection, which will determine the amount of noise present in the signals. Therefore, it is not possible to set a numerical value for the limit of the sensitivity of laboratory-based eddy current measurements, but it can be observed that they will not be as sensitive as the creeping wave ultrasonic technique.

EFFECT OF STRUCTURAL AND INSPECTION VARIABLES ON DETECTION AND QUANTIFICATION OF DAMAGE IN AIRCRAFT STRUCTURES

It is very important to recall that the ultrasonic and eddy current sensitivity values identified in this paper represent only the ability to detect fatigue cracks in structural components. It does not address the quantification of damage, which is the ultimate goal to be achieved with the implementation of CBM. To realize damage quantification, additional analysis of the NDE signals is required. This includes addressing all factors that can affect the NDE measurement, which can be broadly identified as the features of the structure, the inspection technique, and the characteristics of the detected damage.

Using a representative example, these three groups can be further analyzed to identify the details that are included in each of the three major categories. The example shown here is a relatively simple structure consisting of two layers attached by fasteners, as shown in Figure 4. The thickness of each layer typically can vary between 0.04" to 0.35" depending on the location on an aircraft. However, it is possible for the total thickness to be more than 2". The fastener diameter for most fuselage and wing structures ranges from 3/16" to 5/16", though there are fasteners as large as 1.0" in diameter. The defect to be characterized is a corner crack located at the far surface of the second layer.

For this structure, factors to consider for the selected inspection technique include the type and geometry of the probe, the contact conditions with the part, and the general scan plan for either manual or automated scanning. There can be additional factors to consider, especially if specialized inspection techniques are used. The structure introduces several additional factors, such as the material in each layer, the presence and condition of sealant between the layers, the presence of contaminants in the sealant, the condition of the outer surface layer, and the presence of any repairs. The fastener holes and fasteners also contribute to the structural factors. This includes hole geometry, fastener type, fastener material, fit of the fastener in the fastener hole, presence of bushings or other modifications to the fastener hole, plus the proximity of adjacent fastener holes and/or edges of the structure.

In addition to the inspection technique and the structure, the type of damage being detected will affect the signal from the defect. For fatigue cracks, this includes the type of crack, the number of cracks at each fastener hole, the location and orientation of the crack relative to the fastener hole and the structure of the part being inspected, and the

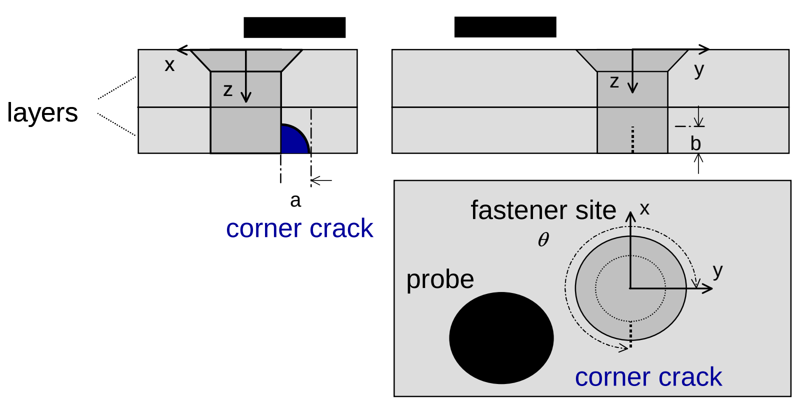

FIGURE 4. Representative two-layer aircraft structure with a corner crack on the far surface of the second layer.

dimensions and morphology of the defect. Other factors that can be present include material located inside the flawed region, such as sealant or drill shavings, that has migrated into an open crack, bushings located in the fastener hole, or if the crack surfaces are pressed together by residual stresses at the crack surface. Thus, over twenty factors influence the NDE signal from a defect when inspecting for fatigue cracks in a multi-layered structure. To address this large number of variables with only a few available measurements, a strategy has been developed to systematically address these factors to pursue flaw characterization, which includes location, orientation and size.

STRATEGY AND OPPORTUNTIES FOR ADDRESSING VARIABLES

To realize the objective of quantifying damage, additional information needs to be extracted from the signals obtained from NDE measurements. The strategy will leverage previous preliminary efforts to determine flaw size in aerospace structures, which focused on EDM notches [10, 11]. It will use a system-based methodology based on using multiple toolsets that will undergo continuous optimization. Sensor development, such as the new class of magnetoresistive sensors and ultrasonic array sensors, combined with the potential to use multiple sensing techniques simultaneously, must be included to obtain as much information regarding the defect as is necessary for its characterization.

The significant areas of opportunity address the current limits of models and data analysis. While eddy current models have progressed significantly to be able to address many aircraft-like structures [12, 13], ultrasonic models typically address only volumetric inspections, are specialized for one or two material/structure configurations, or use ray tracing methods that do not adequately represent complex scattering plus guided and/or creeping waves. Therefore, computer models that can accurately represent the complex structures occurring in aircraft for both eddy current and ultrasonics would be very helpful, as these models would be used to investigate interaction between inspection technique and the structure. Thus, they could greatly reduce the cost of parametric studies while increasing the rate at which these studies are completed. In addition, it is envisioned the models can be used to assist in developing signal analysis techniques that account for the multiple sources of noise and/or interference that affect the NDE modality in the structure, which would lead to enhanced data analysis and classification techniques. This includes model-based classifiers based on inverse methods and/or data fusion.

By combining these improvements to the current state of the art, a model-based damage characterization process can be developed. Note that this process will be very complex and validation studies will require data from real aircraft. Due to the variance that can be observed from real aircraft, such as minor differences in structural configurations as a result of repair and/or modifications, this data is very important to assess the accuracy of the computer simulations, plus provide information regarding noise and scattering features that ultimately could be addressed through much more simplistic classification routines. This could avoid the significant effort to develop computer simulations to provide an exact representation of the noise in a signal when it can be determined that the effect of the noise is minimal on the information needed to quantify damage in the part. However, all these factors will have to be systematically studied to make this determination.

SUMMARY

The objective of the US Air Force to use CBM as a method to sustain its current and future aircraft will require developing techniques to characterize damage that could be present in the aircraft structure. This must be done with NDE methods that can be used, at a minimum, in Depot inspection environment. However, even laboratory experiments have shown damage quantification for structures approaching the complexity of those found in aircraft is not a simple task. All current inspection methods used for US Air Force aircraft detect the presence of damage and do not provide quantitative data regarding the size of the damage, unless there is significant disassembly of the aircraft, such as removing fasteners.

A strategy has been presented to address this shortfall of current NDE techniques. The process must address all the relevant variables that can affect the response from a defect. The strategy will use a systems-based approach to systematically address the variables and determine how they may affect the NDE signal. It will include the use of computer models to assist in developing signal analysis and classification process, plus perform extensive parametric studies to determine which variables need to be addressed by the measurement and analysis technique. The model-based characterization process will require extensive validation studies, which must include data from real aircraft structures to provide an accurate depiction of how the signals are affected by these structures. This development should result in a methodology for characterizing damage in aircraft and input is always sought for concepts, methods, and ideas to facilitate this development process.

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