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Damage Tolerance Management for Aircraft and Rotorcraft Structural Components

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Damage tolerance management of aircraft and rotorcraft components is becoming a necessity. Adaptive structures have a great role to play in the success of implementation of damage tolerance methodologies. However, in current industry practices, there is not widespread application of damage tolerance methods and adaptive structures. The general considerations for damage tolerant management of aircraft and rotorcraft components are outlined, with the focus mainly on rotorcraft dynamic components. Some available and emerging nondestructive evaluation methods suitable for application on metallic components are discussed. Last, cost benefit analysis and formulations that can be useful for future computation of the cost for damage tolerance management of the aircraft and rotorcraft components are described in detail. For widespread acceptance of smart structures and sensors technologies for damage tolerance management, proven studies of such technologies on flight systems and favorable economic benefits are essential. It is envisaged that the outlined criteria and cost benefit analysis for damage tolerance management would enable the adaptive structures community to implement their technologies for industrial applications.

I. Introduction

THE Federal Aviation Administration (FAA) and Department of Defense (DOD)/military are adding damage (flaw) tolerance requirements for the design, certification, and management of aircraft and helicopter structures.[1–6] The requirement for damage tolerance to complement traditional safe life is driven by the observation that helicopter structural cracking and failures, as with the fixed wing aircraft, are often the result of defects, and thus, the safety issue is not with safe-life replacement times but with damage tolerance considerations. Also, it is observed that reductions in cracking problems and the potential for condition-based replacement can reduce life cycle costs by reducing maintenance actions, improving fleet readiness, and extending service life.

The U.S. Air Force has been the leader in requiring crack growth damage tolerant design and has had this requirement for fixed-wing aircraft since the 1970s and for gas-turbine engines since the 1980s. The FAA now requires crack growth damage tolerant design and certification for fixed-wing aircraft, and this requirement was strengthened in the 1998 revision to Federal Aviation Regulation FAR25.571 brought about by review with the Technical Oversight Group on Aging Aircraft (TOGAA). In 1987, the FAA modified FAR29.571 and its Advisory Circular to require either flaw tolerant or crack growth damage tolerant design and certification for rotorcraft structures. An evaluation of these requirements is in progress with FAA and the industry.

TOGAA has strongly recommended the crack growth damage tolerance approach over flaw tolerance, and technical specialists within the FAA also express a preference for crack growth damage tolerance. Many industry engineers have also indicted a preference for crack growth damage tolerance. This preference for crack growth damage tolerance is based on the following issues.

1) Visually detectable flaws as assumed in flaw tolerance may not always precede premature cracking and fractures in rotorcraft components.

2) Types and sizes of flaws are difficult to predict.

3) Consistency in introducing flaws into test specimens and in structural response to the flaws is a concern.

Although the crack growth damage tolerance approach is preferred, the technology and costs for implementation remain a major problem. This research studies the process of determining the feasibility, validity, and applicability of damage tolerance (DT) to the continued airworthiness of existing rotorcraft designs and certification of new designs. This effort involves in-depth analyses and full-scale testing associated with airworthiness issues and the evaluation of damage tolerance methods to design rotorcraft dynamic components. Determining the inspection intervals of a given aircraft component, using the DT methodology requires roughly comparable technological capabilities in five distinct areas.

1) Material fatigue and crack growth properties involves measurements of the basic fatigue crack growth and fracture properties of the material used in the component.

2) Structural degradation modes is in-depth knowledge and understanding of mechanical damages influencing the initiation and propagation of cracks due to fatigue.

3) Fracture mechanics methods are development and appropriate use of fracture mechanics analysis techniques for quantifying fatigue crack growth from an initiating crack and for determining the residual strength-based limit-load condition.

4) Characterization of load spectrum involves quantitative knowledge of the cyclic stresses imposed on the component by the assumed applied loading spectrum.

5) Nondestructive inspection (NDI) techniques involve the ability to cost effectively detect the existence of a cracklike defect in the component.

A key driver of the technology and cost involved in a rotorcraft/aircraft crack growth DT method is the need for reliable detection of relatively small cracks (10–30 mil deep requirement) to achieve reasonable inspection intervals. The intent of this paper is to outline some of the major technical and cost issues, related to

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nondestructive evaluation (NDE) methods in support of a damage tolerance approach. As a fundamental part of an effective DT approach, a review and assessment of current and future nondestructive inspection techniques was necessary. Finally, a cost-benefit analysis framework is outlined for future consideration in evaluating a DT method to design aircraft and rotorcraft structural components.

II. DT: General Considerations

The rotorcraft/aircraft industry needs to determine the feasibility, validity, and application of DT to the continued airworthiness of existing designs and certification of new designs. This effort would involve in-depth analysis and full-scale testing associated with airworthiness issues and the evaluation of DT methods to design rotorcraft and aircraft dynamic and structural components. The purpose of this section is to outline some of the major technical issues to be addressed to envisage DT for metallic components in rotorcraft and aircraft. Determining the inspection intervals of a given aircraft component, using the DT methodology, requires roughly comparable technological capabilities in five distinct areas listed in the preceding section[1–6]: 1) material fatigue and crack growth properties, 2) structural degradation modes, 3) fracture mechanics methods, 4) characterization of load spectrum, and 5) NDI techniques.

A. Crack Growth and Fatigue Properties Database

1. Crack Growth Properties

Crack growth properties are needed in the threshold and growth regimes. Because rotorcraft dynamic components are undergoing high-cycle fatigue, particular attention should be placed on determining the threshold and crack growth rate data near the threshold. Methods for determining threshold stress intensity and the behavior of small cracks are currently being revised in the aerospace industry. Plasticity zones at the crack tip and wake and at specimen edges are now thought to affect small crack behavior and threshold stress intensity values. Additionally, specimen bulk residual stresses are thought to affect the behavior. Efforts should, therefore, directly address these issues to provide the most accurate data possible. As this crack growth data is developed, it could also be included in a readily available fracture mechanics computer code such as NASGRO for consequential analysis.[2–4]

2. Fatigue Crack Initiation Properties

To complement crack growth tests, fatigue tests of as-manufactured and uncracked specimens for identified rotorcraft materials should be conducted. These data are necessary to relate the specific material being tested to potential historical databases and will provide required information relating threshold crack stress intensities to the endurance limits. Data should be developed for standard surface finishes as well as for relevant surface treatments such as shot peening. These data are needed to assess the use of the equivalent initial flaw size concept.

B. Structural Degradation Modes

This database will help in understanding the primary causes for parts removal. Although the effect of damage is premature cracking, all types of damage do not behave as cracks as soon as the damage is incurred. Thus, conventional fracture mechanics models may not be able to predict the full effect of damage. Additional efforts should be performed to understand the behavior of the primary causes of damage. The following three principal degradation modes are detailed next: fatigue damage, corrosion (or environmental deterioration), and accidental damage.[2–6]

1. Fatigue Damage

There are two primary types of fatigue observed for metallic structures on aircraft: low-cycle fatigue (LCF), for example, from flight maneuver and gust loading, and high-cycle fatigue, for example, from vibratory excitation from aerodynamic, mechanical, or acoustic sources.

Crack growth. Monitoring of LCF cracking from preexisting flaws or defects should be an integral part of the inspection and maintenance regimen. Commercial aircraft structures are designed assuming that the maximum probable sized flaw or defect is located in the most critical area of the structure. Safety limits are calculated as the time for a crack to grow from the assumed initial flaw size to the critical size leading to rapid fracture.

Under given initial design operating conditions, stress levels and materials are selected so that the safety limits will not be reached within the life of the airframe. However, operations outside the intended flight envelop or beyond the intended service life could lead to increases in the number of critical areas and could increase the possibility that fatigue cracking will not be detected. This complexity is amplified if the surface has been shot peened. Fatigue damage must be detected so repairs can be made before the crack reaches critical length. If cracks are found that are below critical size, inspection intervals should be shortened to ensure that needed repairs are made before the crack approaches critical length. There are currently no effective means (short of full-scale fatigue testing) to identify new critical areas as they develop as a result of usage. Although it is hard to quantify, as a guidance for the purpose for this paper, the NDE methods should be able to detect crack sizes of 5–15 mil (0.127–0.381 mm) in metallic components and less than a $\frac{1}{4}$ in. (6.35 mm) in composite laminates. These values are regarded as advisories for the evaluation of various methodologies and not an absolute marker.

Widespread fatigue damage. Although a fail-safe structure is designed to tolerate fatigue damage, widespread fatigue damage (WFD) can compromise fail-safe structural design features. WFD is the simultaneous presence of small cracks initiating from normal quality structural details. WFD can exist as multiple-site damage, where cracks are present in the same structural element, or multiple-element damage, where cracks are present in adjacent structural elements.

To maintain airworthiness in fail-safe structure, the onset of WFD must be avoided. The onset of WFD is defined as the point in time when cracks are of sufficient size and density to cause the residual strength of the structure to degrade to where it will no longer sustain the required loads in the event of a primary load-path failure or a large partial damage incident.

Managing WFD requires predicting the onset of WFD in an accurate and timely manner. This involves the prediction of initiation and growth of small fatigue cracks (or the interpretation of full-scale fatigue test data and service fatigue data), the prediction of fail-safe residual strength, and the evaluation of the potential effects of environmentally induced corrosion on crack initiation and growth and residual strength. A number of models and analyses have been developed to assess WFD.

High-cycle fatigue. High-cycle fatigue (HCF), resulting from exposure to high-frequency load cycles from aerodynamic, mechanical, and acoustic sources, is generally handled during initial design for airframes of commercial aircraft, but can represent a serious threat to structural integrity. The amplitude of HCF load cycles is lower than operation load cycles, but the high frequency can lead to significant damage in very short times. HCF conditions can lead to crack initiation in an unflawed structure or rapid propagation from even very small initial flaws. Most of the time, forced response excitations are not eliminated; hence, part sizes are modified to achieve desired life.

Even though excitations that could result in HCF are generally identified and corrected during initial design and structural testing, changes in 1) the response of the structure, for example, due to wear, corrosion, loose fasteners, repairs, and LCF crack growth, or 2) the operational environment of the aircraft could lead to HCF in service. Because of the nature of HCF damage, crack initiation and growth must be avoided.

2. Corrosion

The predominant environmental damage mechanism for metallic structures is corrosion.[2] The main concern with corrosion of metallic airframes is that, if left undetected, there is the potential for synergy with other degradation mechanisms that could, in turn, lead to structural failure. For this reason, significant effort and expense is focused on the inspection and repair of corrosion damage.

There are a wide variety of corrosion types that routinely occur in aircraft structures. The different types of corrosion can have very different characteristics and consequences, making detection and assessment very complicated. Corrosion may, or may not, induce cracks depending on the type of material. Though NDE for corrosion detection is becoming available, corrosion is still often detected using visual inspection methods.

Unfortunately, visual inspection has been shown to have inconsistent reliability, even with experienced inspectors. Because of the difficulty in detecting and characterizing corrosion, the commercial airline industry has elected to manage corrosion primarily through prevention and control. The commercial aircraft industry has developed corrosion prevention and control plans for each specific airplane type. In the developing of these plans, the industry established standards to assess corrosion severity, ranging from level 1, where corrosion can be repaired with no structural consequences, to level 3, where corrosion presents a major or systematic threat to airworthiness.

The intent of corrosion prevention and control plans is to ensure that corrosion will not be allowed to progress to the point where it will be a threat to structural safety, for example, no greater than level 1, and to reduce operator's maintenance costs. Corrosion that is found is exposed and repaired, and corrosion prevention coatings or compounds are reapplied. The strategy of monitoring for corrosion damage is to focus on early detection of incipient corrosion, or, preferably, detection of when the corrosion prevention scheme has failed. Fatigue tests of corroded specimens would establish a basis for understanding and developing a DT approach to minimize cracks due to corrosion. A monitoring approach would have two objectives: 1) identify and correct corrosion damage before it becomes a threat to structural integrity and 2) enable inspection for hidden corrosion without unnecessarily disturbing intact structure. The determination of inspection intervals would depend on the rate at which corrosion develops under operational environmental conditions. Therefore, historical corrosion rate data would be a very useful database to establish.

3. *Accidental Damage*

Accidental damage is the one structural degradation mechanism that is not considered to be an aging mechanism. This damage could be result of unexpectedly severe operating conditions, operations and maintenance handling, foreign object damage, or thermal and environmental exposure. Examples of some of the rare events that could lead to accidental damage include unexpected flight or maneuver loads and overload from actuation system failures, foreign object damage, and damage from in-flight failure of other components.

These damages, such as scratches or dents, which occur during field service, probably do not necessarily produce cracks immediately. However, it is critical to understand how cracks develop and grow from these locations. The behavior and growth of cracks from these types of damage are particularly complex because of their unpredictable nature and residual stress effects near the threshold. In-depth understanding of the behavior of small cracks in a region where local residual stress fields exist is critical. Fatigue testing of damaged samples, observing the initiation and growth of cracks, should be conducted extensively for key rotorcraft dynamic components. These tests combined with a model describing the residual stress fields are critical to understand the development of cracks in these cases.

C. Fracture Mechanics Methods

The need for specialized fracture mechanics-based computer models that accurately predict the initiation and growth of fatigue cracks in three dimensions, with local residual stresses and under spectral loading, is motivation for the DT approach. Current computer codes may not be readily applicable to rotorcraft components and may have to be refined and validated by the rotorcraft industry. A number of crack growth codes already exist and may partially satisfy these needs. However, further studies and investigations are required to determine what tool(s) would fulfill all of the needs for a DT assessment.

The fracture mechanics techniques developed at the University of California, Los Angeles, (UCLA) are currently being validated by the rotorcraft industry in actual and simulated fatigue crack growth applications. The FAA-supported rotorcraft damage tolerance research being conducted at UCLA has produced a methodology known as automated, global, intermediate, and local evaluation (AGILE). AGILE is a suite of software tools that was developed for the automation of hierarchical analysis of complex structures. The software is used to evaluate the fracture parameters of two-dimensional and three-dimensional cracks. Because rotorcraft structural components accumulate cyclic loads at very high rates, very small arbitrarily shaped and warped cracks can occur. AGILE-3D, has been developed to determine the stress-intensity factors around the periphery of arbitrarily shaped and oriented cracks in rotorcraft drive system dynamic components. AGILE-3D additionally allows elastic–plastic fracture mechanics parameters to be determined for conditions in which conventional linear elastic–fracture mechanics procedures are invalid. Although it will have a broad range of usage, AGILE-3D is primarily aimed at rotorcraft drive system components such as those included in the configuration of multibladed rotorcraft main rotor system.[1]

The finite element alternating method (FEAM) is used to evaluate the fracture parameters due to its efficiency. FEAM allows the user to calculate the fracture parameters very accurately without excessive computational power. However, the FEAM software is currently limited to a pure two-dimensional plane or three-dimensional solid structure with uniform material properties. The implementation cannot handle a large-scale model efficiently. Combining FEAM with a conventional finite element approach using a hierarchical analysis strategy overcomes the drawbacks by performing a series of multiple-stage solutions as follows.

1) The whole structure is analyzed using a conventional finite element method.

2) A subregion of the structure containing the crack with the appropriate boundary conditions is extracted.

3) The subregion is solved using FEAM, and the appropriate fracture parameters are calculated.

Shot peening and other forms of surface treatment that induce compressive residual stresses to retard fatigue crack growth are important in rotorcraft. The research that has been done to date has generally been based on linear elastic fracture mechanics. However, because these surface treatment processes deform the material in a nonelastic manner, an elastic–plastic approach is necessary. Such an approach would first determine the residual stress state, induced by the various procedures. The second stage would devise an elastic–plastic fatigue crack growth computational analysis model that would be valid for cracks moving through the inelastically deformed regions.

A second key area for further research is one that would enable fracture mechanics methods to be directly applied when a body with a hole, dent, flaw, or another form of stress riser is subjected to cyclic loads that generate a crack. What is needed is the capability that, perhaps embedded within a localized model in a hierarchical computational procedure, formulates and quantifies the processes of ductile void nucleation, growth, and coalescence that reflect the manner in which cracks incubate and, eventually, start to propagate.

Studies are being conducted to investigate DT methods for gas-turbine blades that experience significant HCF. The fixed-wing industry has implemented a DT lifing methodology. Although the fixed-wind load spectrum is quite different from the rotorcraft spectrum, it would be valuable to determine the applicability of these methods. Probabilistic methods can also be explored to assess the impact of damage in critical areas of rotorcraft dynamic systems. The DARWIN computer code has been developed to address these issues for the gas-turbine industry. Its use should be explored for the propeller industry.

D. Identification of Load Spectra

Representative load spectra describing a panel of rotorcraft mission profiles, that is, stress history, should be established in detail. These spectra will also be influenced by environmental conditions, such as temperature, at takeoff and/or landing. The development of standard load spectra is required for adequate test conditions for DT methods and in establishing appropriate inspection intervals. Load-monitoring systems would provide a database for establishing actual usage and load spectra.

E. NDI Techniques

NDI methods are essential to the application of a rigorous DT approach. Characterizing the selected inspection method sensitivity using probability of detection (POD) curves for each component material, surface finish, geometry, and accessibility, as well as crack location and type, is critical. Specific NDI methods may need to be developed to detect reliably the size and types of damage for rotorcraft components, down to 0.010-in. crack depth or less. The rest of this paper will focus on the NDE aspect of a DT approach to designing rotorcraft dynamic components.

III. Assessment of NDE Techniques

A. Some Mature NDE Technologies

In this section, current and emerging NDE methods and capability for detection of small cracks in rotorcraft dynamic system components are described. Generally the potential fracture modes in these components are in single load paths, and to achieve reasonable inspection intervals of 1000 flight hours or more, it will be necessary to detect cracks in range of 10–50 mil in depth. In some instances where an inspection process is relatively quick and inexpensive, it may be more cost effective to have more frequent inspections for larger cracks.

NDE techniques, which would be employed in periodic inspections, have to able to detect different types of flaws. Otherwise, it would be time consuming and cost prohibitive. NDE technology could not be successfully implemented unless it is easily usable by the maintenance crews and the results are interpreted efficiently and cost effectively. The visual inspection (VI) process, widely accepted and implemented currently during periodic inspection,[5] cannot be fully replaced immediately. Hence, the objective of the implementable technology would be to complement the VI process. Therefore, imaging processes associated with scanning technologies would be promising because the maintenance crew could easily understand the tools. The in-situ smart sensing technologies are best left for onboard monitoring, which can become part of the health usage monitoring systems technology in the future.

1. *Current Inspection Practices*

The fluorescent penetrant and magnetic particle are the some of the primary methods of NDE employed by the aircraft and rotorcraft industry. Fluorescent penetrant inspection (FPI) is a nondestructive method of revealing discontinuities that are open to the surface by capillary action. The method can be used for detection of all types of surface cracks, laps, porosity, shrinkage areas, laminations, and similar discontinuities. Depending on material and crack properties, 30–75 mil deep cracks can be detected. Magnetic particle inspection is a method of locating surface and subsurface discontinuities in ferromagnetic materials. It is based on the fact that, when the component under test is magnetized, magnetic discontinuities that lie in a direction transverse to the direction of the magnetic field will cause a leakage field to be formed at and above the surface of the part. The presence of this leakage field is detected by the use of finely divided ferromagnetic particles applied over the surface. The magnetic particle method is a sensitive means of locating small and shallow surface cracks in ferromagnetic materials as well as subsurface flaws. The major limitation of the method is that the magnetic field must be applied in a direction that will intercept the principal plane of the discontinuity; this sometimes requires two or more sequential inspections with different magnetization. Depending on crack properties, 70–125 mil deep cracks can be detected.

2. *Probability of Detection Calculation*

The focus of this section is on producing estimates of specific fatigue crack sizes in metallic surfaces that are reliably detectable with eddy current inspection (ECT) and liquid (fluorescent) penetrant inspection. Only preexisting NDI data available from external and internal sources were employed in the analysis; no new NDE measurements were performed.

The reliability of NDE procedures can be quantified in terms of POD with an associated confidence bound. When a manual NDE procedure must be performed on an aircraft component, the FAA typically requires that the procedure must have a 90% POD with 95% confidence for a particular crack size specified by a. A 90% POD of a with 95% confidence implies that a particular inspection procedure, for example an ECI procedure, has been shown through experiment to detect reliably a crack size a 9 out of 10 times with the confidence that any particular observation has only a 1 out of 20 chance of having a POD(a) less than 90% (Refs. 6 and 7).

Standard depth of penetration for ECI applicability in titanium components. The following empirical equation and graph Fig. 1 give a rule of thumb for frequency bandwidth of ECI to be carried on depending on the depth where a subsurface flaw is located in a given titanium panel. It also gives the information about the effective depth of ECI operability for a given frequency. Any value near to and on the surface (indicated by 100) should be neglected.

Standard depth of penetration is calculated to be the point in the material where the eddy current is dropped to 37% of the strength

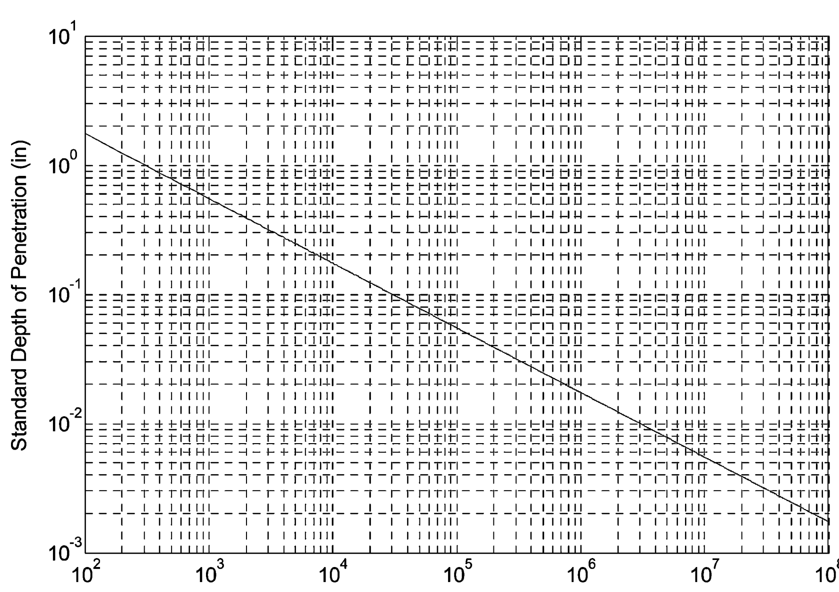

Fig. 1 Frequency vs standard depth of penetration.

at the surface. The effective depth is three times the value. The standard formula for computing the standard depth of penetration in nonferrous materials is

$$d = 1.9685\sqrt{172.41/f \times \text{IACS}} \quad (1)$$

where d is the standard depth of penetration (inches), f is the frequency (hertz). Conductivity is measured as the % of IACS. The conductivity of titanium (%IACS) = 2.2. The conductivity of the material may change with temperature, heat treatment, cold working, etc.

ECI for surface and subsurface cracks. Service-induced cracks in aircraft structures are generally caused by fatigue or stress corrosion. Both types of cracks initiate at the surface of a part. If this surface is accessible, a high-frequency ECI can be performed with a minimum of part preparation and a high degree of sensitivity. If the surface is less accessible, such as in a subsurface layer of structure, low-frequency ECI can usually be performed. ECI can usually be performed without removing surface coatings such as primer, paint, and anodic films. ECI has the greatest application for inspecting small and localized areas where possible crack initiation is suspected rather than for scanning broad areas for randomly oriented cracks. However, in some instances, it is more economical to scan relatively large areas with eddy current rather than strip surface coatings, inspect by other methods, and then refinish. The ECI requirements for surface and subsurface inspection to follow is summarized from the FAA report.[8]

For surface inspection, the following are typical eddy current equipment requirements.

1) Instruments must meet the liftoff and sensitivity requirements of the applicable NDI procedures. The frequency requirement is generally 100 Hz–200 kHz.

2) Many types of probes are available such as flat-surface, spring-loaded, pencil, shielded pencil, right-angle pencil, or fastener hole probes.

3) A reference standard is required for the calibration of eddy current test equipment. A reference standard is made from the same material as that which is to be tested. A reference standard contains known flaws or cracks and could include items such as a flat surface notch, a fastener head, a fastener hole, or a countersink hole.

ECI techniques are used to inspect for subsurface cracks. The following are typical eddy current equipment requirements for subsurface crack inspections.

1) Use a variable frequency instrument with frequency capability from 100 Hz to 50 MHz.

2) The probe used would be a spot, ring, or sliding probe.

3) Use a reference standard appropriate for the inspection being performed.

3. *FPI Capability Assessment*

FPI is a relatively old NDI modality that is in greater widespread use than ECI, but generally has lower crack detection sensitivity at least compared with automated ECI. In contrast, manual FPI systems generally require a much smaller initial capital investment than ECI and are simpler to use and interpret. Typical FPI techniques require that a liquid fluorescent penetrant be applied to a clean part surface. After the penetrant is allowed to adsorb to features such as cracks and laps, the excess penetrant is then rinsed from the surface. Next, the surface is exposed to UV light, which causes any trapped penetrant to fluoresce. Traditional FPI methods use a divergent light source, such as a hand-held UV lamp, to excite the penetrant. Observation of the fluorescent indications is conducted either visually or, more recently, with a charge-coupled device camera. FPI is typically a manual operation that uses direct visual inspection to detect the surface breaking cracks filled with fluorescing penetrant.

B. Some Emerging NDE Technologies

For successful implementation of a DT management (DTM) program, early detection of cracks is absolutely essential. The NDE ground inspection turnaround time and cost can be decreased considerably by inspecting the failure modes as predefined from experimental results. These probable failure locations are known as hotspots or critical zones. The NDE requirements for periodic inspection during in-service and at the retirement time of the component can comprise a combination of NDE methods in addition to the VI method. For early detection of cracks of size 5–20 mil at 10–50 mil depth, some of the more advanced and emerging NDE methods need to be applied.

1. *Meandering Winding Magnetometer Eddy Current Sensors*

ECI (magnetically inductive materials), FPI (mostly for surface cracks that open up) and thermosonic inspection (thermally conductive materials) could be effective for NDE of rotorcraft and aircraft dynamic components. Recent research in the eddy current method, which promises higher accuracy and faster scanning, includes development of pulse eddy current probe created at academic institutions[9,10] and at NASA Langley Research Center[11] and eddy current holography.[12] JENTEK Sensors, Inc., has developed surface-mounted eddy current sensors [eddy current meandering winding magnetometer (MWM) sensor arrays] for detecting small cracks for difficult to access locations.[13] These sensors can be custom made for detecting internal (subsurface) and surface early fatigue cracks and corrosion damages in rivets, bolt joints, holes, and threads, as well as on curved and straight surfaces. These MWM arrays could either be flex mounted or permanently mounted and can be scanned remotely. Unlike strain gauges, which fail during crack initiation and growth, MWM arrays can be flex mounted and local high strain does not affect the performance of the sensor array. These sensors are customizable to the structure or to the part of the structure that needs to be monitored. For accessible areas, MWM sensor arrays are flex mounted (temporarily mounted) and then moved around to get a wider scanning area coverage. When the sensors are flex mounted, the software generates a two-dimensional image scan of the scanned area where a fatigue damage can be clearly detected by the change in the contour patterns. For inaccessible areas, the sensors are customized to cover a wide area and are permanently mounted. The tail of the sensor is made long enough so that the connecting port is accessible for connecting wires to the datalogger during inspection. This avoids the need for wires to be permanently attached and, thus, is convenient for rotating components. For permanently mounted sensors, the software generates a B-scan-type image, where a linear line indicates no damage and cracks and other damages generate bumps in the B-scan image. An initial check using the associated software, before the inspection, is performed for sensor validation. If the sensors permanently mounted in the inaccessible areas are not working, then disassembly of the component may be required to affix new sensors. The advantage of using this type of sensing technology is that cost prohibitive and time consuming disassembly of the structure can be avoided while NDE inspection is being done.

The Federal Aviation Administration/Airworthiness Assurance Nondestructive Inspection (NDI) Validation Center, as a third party, conducted investigations on the MWM eddy current sensor arrays for cracks in as-manufactured titanium engine disks.[14] Limited statistical analyses of the scanning results indicate that the MWM array can detect cracks between 0.015 (15) and 0.020 in. (20 mil) long (crack length at the surface) with a false-call rate below 5%. This is based on the estimated 90/50 POD inspection reliability (90% POD at 50% confidence level). The highest FPI detection limit for cracks in as-manufactured titanium engine disks at the 90/50 level is 0.020-in. (20-mil) depth. This size corresponds to 0.020 (20) deep by 0.040 in. (40 mil) long surface cracks or 0.20 (20) by 0.020 in. (20 mil) corner cracks. This level of performance is not typically achieved by FPI. Based on this study,[14] for appropriate locations on engine disks, eddy current MWM arrays have the potential to replace fluorescent liquid penetrant inspections (FPI) in production and in-service, except that MWM arrays only work for certain materials and are discrete sensors. FPI gives broader coverage and works for most materials.

2. *Pulse Thermography*

Pulse thermography NDT with infrared imaging[15] (Thermal Wave Imaging Systems) and thermographic scanning with ultrasonic input excitation known as thermosonic (Indigo Systems) are two NDE technologies that are very promising in terms of locating surface and subsurface defects and cracks in composites and metallic structures. Whereas pulse thermography is very useful for detecting underlying cracks, delamination, and corrosion, it is not adequate for detecting vertical cracks (cracks lying perpendicular to the source of thermal pulses). The ultrasonic pulse input excitation helps the vertical crack to open and helps in detection by thermography. An analogous technique now gaining acceptance in industry is laser ultrasonics for similar NDE applications. The U.S. Navy is in the process of implementing this NDE technique for its existing aircraft fleet for detection of corrosion. Thermography and ultrasonic scanning are useful NDE methods for inspection at the manufacture and overhaul or for infrequent test down inspections. The main advantage of these scanning technologies is their ability to scan a large area in a short period of time and to generate a visual image of the area. This method helps the maintenance crew easily detect cracks and flaws. A full scale noncontact ultrasonic and thermographic scanning is also very useful to find surface and subsurface manufacturing flaws at the end of the production line. For the Joint Strike Force competitive bidding, both The Boeing Company and Lockheed Martin used noncontact ultrasonic and thermographic scanning for their pilot aircraft components as part of the contract. Similarly, NASA did the same for all of the shuttle parts, after the Columbia tragedy. Pulse thermography or thermosonic scanning and remote ECI using MWM eddy current sensors can be very useful for quick, noninvasive, inexpensive NDE of components with or without disassembly.

3. Summary

On a cautionary note, not enough information is available on the maturation of these technologies today, as applied to NDE of metallic structural components. These NDE technologies, thermosonic and MWM eddy current methods, may be capable of detecting small cracks in range of 5–10 mil. However, with the currently available knowledge of these NDE methods, we cannot make that claim without performing adequate testing on the various rotorcraft crack locations. These tests would involve generating appropriate POD curves for each location, with ECI and thermosonic equipment. For the MWM sensor arrays to be applicable, adequate fatigue testing has to done to ensure that the sensors do not fail during the operating life of the component, especially if placed in inaccessible areas.

IV. Cost Benefit Analysis

A. Introduction

A major challenge to the airline industry is that it must maintain a high standard of safety with a fleet of aircraft that is increasing in age in an environment that is economically driven and highly competitive. The average age of the commercial fleet of aircraft has risen from 4.6 years in 1970 to 12.7 years in 1989. As the current fleet is aging, the number of maintenance requirements to assure the continued airworthiness of the fleet is and will be increasing. Cost-effective methods of attaining the required safety standards are critical to operators in today's economic climate. New methods of inspection may prove to be feasible to address the growing concerns of maintaining an aging fleet of aircraft at a cost that is acceptable to the industry. This section addresses NDE techniques used for inspecting aircraft.

B. Cost Benefit Model

This section should serve as a methodological guideline for the measurement of costs and benefits of adopting a given NDE technique for rotorcraft structural inspection. The cost benefit analysis would measure the future stream of benefits and costs to implementing modified inspection requirements relative to a DT approach compared to current inspection requirements using the flaw tolerance approach for the S-92 series. The complete evaluation of the financial benefits net of costs for an individual aircraft operator is rather complex and will not be completed in this paper. In the analytical framework, parameters such as the costs and benefits to the NDE user, the useful life of the NDE technique, and the rate used to discount the future costs and benefits to their present values, should be included and are required to apply the model. The analysis should include the net benefit to society related to adopting modified inspection requirements, especially because this investment decision may be mandated by FAA rule for increased rotorcraft safety. The base case scenario with which to compare the net benefits of additional inspection procedures is assumed to be the recommended inspection process defined by the flaw tolerant method. This base case is the most likely to occur if the investment is not undertaken, that is, if DT supported by NDI is not adopted. The net present value (NPV) calculation is made as follows:

$$\mathrm{NPV}_i = \sum_{t=0}^{T} \frac{(B_i - C_i)}{(1 + r_i)^t} \tag{2}$$

where T is the useful life of the technique, B benefits, C costs, and r discount rate. If the NPV is positive, the future stream of benefits outweighs the future stream of costs and the NDI investment will yield a positive return.

Only avoidable and incremental costs and benefits should be measured and accounted for. Costs and benefits are avoidable if they are directly attributed to the additional NDI inspection. These costs exclude sunk costs, costs incurred before to the evaluation. Costs and benefits are incremental in reference to a baseline scenario or base case, that is, current NDI inspection procedure without changes. Both costs and benefits should be measured in a common unit of value. Constant dollar is an example of measure because it nets out all effects of inflation. In this case, future values are expressed in terms of value of money in that specific year. However, it is important to recognize that it may not be appropriate or adequate to assign a dollar value on certain costs and benefits.

The economic useful life of an NDE technique is the period in which the technique fulfills the requirement for which it is employed at the lowest achievable cost compared with alternative techniques. An accurate estimate of the economic life and life cycle costs of the NDE technique must be made to determine the time period over which the investment should be evaluated in the model. Therefore, it is imperative that the NDE techniques be sufficiently developed before they are examined in a cost-benefit analysis framework.

A number of considerations should be examined to define the discount rate to use for the cost-benefit analysis. A conservative assumption would state that all costs are incurred at the beginning of each year and all benefits appear at the end of each year. This assumption would yield the largest disparity in time between the payment of costs and receipt of benefits. Another assumption could be that all costs and benefits are incurred at the middle of the year or continuously incurred throughout the year. The most appropriate assumption should be made on a case-by-case basis.

C. Data Requirements

1. Costs

Accurate measurement of costs must take into account the life cycle costs of any NDE technique, including 1) capital costs, that is, investment costs in both physical and human capital and any relevant research and development; 2) operating costs, which are continuing costs of employing the inspection technique over the lifetime of the technique and may vary with the number of inspections; and 3) termination costs, that is, any costs associated with the retirement of the new equipment at the end of its useful life (such as dismantling cost, scrap value, hazardous waste processing, etc.).

However, because some techniques can require a large investment for a relatively low utilization rate, the optimal solution is to lease or contract out the equipment. In this case, the cost-benefit framework described is not the most appropriate methodology to evaluate the worthiness of the decision.

Capital costs. These costs are considered fixed to the extent that they will not vary directly with the number of inspections performed. A way to decompose this cost is as follows: 1) costs associated with research and development; 2) costs associated with physical capital costs, such as investment of durable equipment, facilities and tools, with transportation required to get equipment to sites and additional cost of space alteration in the physical structure of the inspection site; and 3) costs associated with human capital costs, such as initial training of personnel to use NDE equipment, including wage, instruction, and travel.

Operating costs. Operating costs are variable costs varying with the number of inspections conducted and can be divided into continuing costs and personnel costs.

The first continuing costs due to use of disposable equipment and materials. These continuing expenses incurred throughout the lifetime of the technique will vary with each NDE technique. As an example, the cost of crack inspection with penetrant is sensitive to the number of inspections because the tool used is disposable. However, the crack inspection using eddy current techniques utilize a durable piece of equipment, involving relatively smaller disposable cost.

The second continuing costs are those costs of preparing the aircraft for inspection, such as stripping and reapplying paint or decals, isolating aircraft for hazardous procedures, and disassembling parts requiring labor and material costs to be incurred to perform inspection accurately.

The first personnel costs are the annual costs of personnel required to perform the inspections, including vacation time, overtime, sick leave, life insurance, and health and retirement benefits. Detailed descriptions of employee working practices could be found from FAA publications or manufacturers' information.

The second personnel costs comprise the retraining costs to maintain and advance new and existing personnel skills, due to updated and more sophisticated equipment. These costs should be examined on a case-by-case basis because they may be very variable and case dependent.

The third personnel costs are the productivity costs, which could improve depending on the flexibility in job allocation within a facility. If NDE inspectors are expected to perform various tasks and visual inspectors and maintenance technicians can be cross trained to do some NDE tasks, the improved efficiency of quicker inspections could be realized. This gain depends highly on work rules flexibility proper to each facility.

In this case, NDE techniques could be advantageous in two specific situations: 1) more flexible work assignments, allowing inspectors to perform wider variety of tasks and 2) simplified operating equipment and result interpretation to enhance flexible work assignments.

Other costs. These costs should be examined on a case-by-case basis and include 1) private costs of the manufacturers associated with the production of the NDE technique, such as equipment, software, and would be refined during validation and field testing; 2) costs to the government due to any increase/decrease in regulatory functions or factory inspections; and 3) negative external effects on society, such as the emission of pollutants, hazardous materials, risk of exposure to unsafe materials, decreased levels of safety, and increase in noise levels.

Expected cost formula. The expected cost of fracture, inspection, and repair in each usage interval could be summarized by the following equation:

$$\begin{aligned} E(c) &= K \times N \times C_i \longleftarrow \text{inspection} \\ &+ K \times N \times P(\Delta a_1) \times C_{r_1} \longleftarrow \text{repair} \\ &+ K \times N \times P(\Delta a_2) \times C_{r_2} \longleftarrow \text{replacement} \\ &+ \text{POF}_A(t) \times N \times C_F \longleftarrow \text{fracture/aircraft loss} \end{aligned} \tag{3}$$

where

$E(c)$	=	expected cost in each usage interval
$\text{POF}_A(t)$	=	probability of fracture (POF) for single aircraft
$P(\Delta a_i)$	=	proportion of detected cracks in interval Δa_i
K	=	number of repair
N	=	number of aircraft in fleet
C_i	=	cost of inspection
C_{R_i}	=	cost of repair/replacement in interval Δa_i
C_F	=	cost of fracture

Cost assumptions are listed in Table 1.

Table 1 Cost assumptions

Item	Amount, $
Labor rate per hour	100
NDI inspection time per component, 16 h	1600
Repair (0.04-in. crack), 6 h	600
Engineering/repair, $0.04 < c < 0.1$ in. crack, 50 h	5,000
Component replacement, $c > 0.1$-in. crack	Component cost
Aircraft loss	Cost of aircraft
Durability and damage tolerance analysis	Cost of finite element analysis

2. Benefits

Some benefits can be quantified in monetary terms, whereas others may not be so easily translated into dollar figures, such as increased probability of detecting flaws and long-term benefits that shift the way the industry approaches structural integrity. Some of these benefits cannot be quantified without strong assumptions about future implications for NDE technology. These nonquantifiable benefits can be as or more important than quantifiable benefits and should not be omitted in the analysis. If a factor is not taken into account, its implicit assigned value is zero, which may not be appropriate for the decision making process. The benefits are listed next in decreasing order of quantifiability.

Costs that may decrease with the following factors. First is decreased labor hours required for inspection. An inspection technique that decreases the time it takes to perform inspections will decrease the inspection cost in labor cost and aircraft downtime. This reduction could be come from inspection techniques that would enable inspectors to examine areas that would otherwise require dismantling or where VI could be applied before mechanical inspection. Less preparation would be needed to perform the inspection. In addition, it could also be achieved by NDE techniques that would enable quicker and more accurate inspections, that is, shorter inspection times. Furthermore, one NDE technique might enhance the detection performance of another NDE and, thus, reduce the need for labor-intensive tasks. In this latter case, the number of personnel required to perform the inspection is minimized.

For instance, methods that are bulky and cumbersome to employ may reduce the labor cost of conducting large-scale inspections where substantial economies of scale can be realized. However, these methods may not be cost effective for spot inspection on the line where the cost of mobilizing the equipment could be high. Total labor hours for a standardized level of inspection will be used to account for both shorter inspection times and decreased personnel requirements. As a result, a standardized definition of the various types of inspections performed and a comparison of labor hours between techniques will be required for a detailed analysis to determine the optimal strategy for the use of NDE techniques for a DT approach.

Second is less frequent inspections are required. An inspection technique that can improve the probability of detecting flaws has the potential to increase the time interval between inspections. Aircraft manufacturer repair manuals specify the maximum time intervals between inspections required to detect a flaw before reaching a critical size (as determined by selected fatigue life approach method). Techniques that detect smaller flaws and/or with higher POD would allow less frequent inspections without affecting overall reliability. This result presumes that POD data are available for the NDE techniques and application considered, which is not the case here.

Third is more efficient labor costs. An inspection technique can reduce the per unit labor cost of performing inspections if it can be used by lower skilled personnel. Current work on NDE techniques that are more user-friendly is being explored. Some of them are elaborated in the dynamic component sections.

Fourth is decrease in number of false positive detection. An inspection technique that delivers more accurate detection could reduce the probability of a false alarm, decreasing the cost associated with false calls. Therefore, improving the detection method, yielding more dependable results and reducing the need for unnecessary disassembly or retest, would decrease the cost of inspection.

Last is increased inspection confidence. A less tangible benefit of an inspection technique producing more reliable results is the increased confidence in the inspection outcomes. These improved detection methods could generate considerable enhancement in the efficiency level of inspectors. Although this factor is more qualitative, it is important to account for because it would enable the workforce to be redeployed or reassigned to more productive tasks.

Retirement of equipment with scrap value. An assessment of the relevance of the scrap value of retired capital should be completed on a case-by-case basis. This termination cost is usually negative. Estimates of the surplus value of equipment must be derived from accounting records and observable market value.

Increase in consumer surplus. There are two ways in which a new NDE technique could increase consumer surplus. The first results in lower consumer prices because any decrease in unit cost of inspection can be passed on by the industry to consumers. Second, the technology could result in improved safety levels and quality of products and services. Estimating this surplus requires information on consumer demand curve, including price elasticity of demand.

Increase in POD. As the probability of detecting flaws in an aircraft structure increases, the probability of an accident occurring should decrease. Thus, expected cost incurred from future accident will lower. To estimate the savings in the cost of accidents, the following parameters must be determined:

First, cost of future accidents depends on the values of aircraft equipment loss, of injuries, of loss of human lives, and on the costs of third-party damage and accident investigation. The expected cost of future accidents is adjusted by the probability of occurrence. Thus, the relationship between the probability and cost of an accident occurring must be known.

Second, the relationship between the POD and the probability of an accident occurring is an assumption. There is no existing model in the literature that precisely defines this relationship.

In conclusion, it is impossible to quantify the monetary value of improved safety because the relationship between POD and of accident is not quantified. However, the cost saved by conducting less frequent inspections when using an NDE technique with higher POD serves as a way to measure indirectly the value of improved safety. Consequently, POD curves of varying flaw sizes for a specific NDE technique are key to the evaluation.

External benefits. Individuals, institutions, and industries that do not participate directly in the market for which the NDE technique is developed also gain from the technology advancement. Leverage to nuclear power and defense industries or to the infrastructure maintenance industry would be beneficial. Although, these benefits are difficult to measure, data availability on the impact of technology spillover should be assessed on a case-by-case basis.

Long-term benefits. In the long run, the use of NDE technology could contribute to improving aircraft maintenance practices. As suggested by a number of research studies, the shift to a DT philosophy as a basis for aircraft maintenance can be seen as a shift toward a more efficient allocation of resources. The emphasis is transferred from redundancy to inspection to gain more information regarding the integrity of the aircraft. The potential result is an aircraft with lighter weight, lower fuel burn, emitting less pollution with an assured life.

A fully developed NDE system could affect maintenance procedures by creating more specialized maintenance plans for each aircraft type. The result may be lower long run maintenance costs by causing detection of flaws at an earlier stage when they are less damaging, less costly, and easier to repair. With more reliable inspection techniques, the frequency intervals between mandatory inspections could be relaxed and determined by the condition of the aircraft rather than by fleet-wide criteria. The effects on maintenance practices can eliminate some of inefficiencies caused by the redundancy and lack of foresight regarding maintenance.

In some cases, a more thorough maintenance and inspection plan can actually extend an aircraft's life by attracting attention to flaws before they have a destructive effect on the rest of the aircraft. Advanced scheduling decisions could be made according to future maintenance needs and a more accurate prediction of the lifetime of the aircraft could be made. A more efficient system to scheduling aircraft downtime could then be developed.

In addition, NDE could contribute to the future development of models of fracture mechanics for aircraft structures. The data collected through NDI could generate a more accurate depiction of the growth path of corrosion or the complex relationship between different types of flaws.

3. *Additional Issues*

The measurement of costs and benefits may not yield a specific value but rather a range of possible values. The NPV values may not be only attributable to uncertainty, but also to heterogeneity, such as collection of base case data. The large number of operators in the industry and varying work practices suggest that data would vary from one source to another. Different fleet profiles and routines of maintenance and inspection represent specific needs, not uniform across the industry. In addition, some DOD depot sites elect to contract large maintenance and inspection to third-party maintenance facilities. Some preliminary evidence suggests that the costs of inspection vary widely. Collection of data would also be a difficult and expensive task. Therefore, a representative group of characteristics should be defined as a benchmark for comparison purposes. Such characteristics could be the type of inspection performed, the type of aircraft (age, size, model, manufacturer), environmental conditions to which the aircraft is exposed, and the working practices of the service.

Because there is high uncertainty related to the realization of the benefits listed in this section, it is not advised to estimate their monetary value. However, their feasibility should be examined, in relation to adequate and detailed fracture mechanics analyses, for the specific NDE technique considered. This cost-benefit analysis framework is intended to provide a complete view of what elements are involved to consider fully a combined DT/NDE approach to rotorcraft certification.

V. Conclusions

The FAA has long been aware of the potential beneficial impact that DT could make in regard to the operational safety of aircraft and rotorcraft. Efforts have been made over the past two decades to incorporate it into its regulations. However, largely because of a general perception that the DT methodology developed for fixed-wing aircraft would likely lead to significant weight penalties and reduced lifetimes in the more demanding conditions occurring in rotorcraft, this DT approach incorporation has not been done. The main barrier to the adoption of DT for rotorcraft, the need to quantify crack growth from small and nonplanar cracks and noncracklike defects that occur in rotorcraft in the form of corrosion pits, dents, scratches, and other blunt-ended damage, is being pursued to enable this to be accomplished. For widespread acceptance of smart structures and sensors technologies for DTM, proven studies of such technologies on flight systems and favorable economic benefits are essential. It is envisaged that the DT considerations and the cost benefit analysis for DTM outlined in this paper would enable adaptive structures community to implement their technologies for aerospace applications.

To address the legitimate concerns associated with full use of DT, the FAA has undertaken a cooperative research program to establish rotorcraft DT technology. Whereas additional challenges must be addressed with further work, the prospects for the routine use of DT for rotorcraft safety of flight applications, in conjunction with current safe-life and fail-safe procedures, appear to be outstanding.

Major features of this study are summarized as follows.

1) General considerations for DTM of aircraft and rotorcraft components have been described in detail.

2) Available and emerging NDE methods, which are suitable for application on metallic components, have been discussed.

3) The cost benefit analysis and formulations have been described in detail, which can be useful for future computation of the cost for DTM of rotorcraft dynamic components.

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