THE AGING AIRCRAFT FLEET A CHALLENGE FOR NONDESTRUCTIVE INSPECTION

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INTRODUCTION

Since the Aloha aircraft accident, all components of the aircraft industry have made a massive effort to ensure the continued airworthiness of the air carrier fleet under the purview of the FAA.

In an effort to coordinate these activities, the FAA hosted an International Conference on Aging Aircraft in June, 1988. From this conference the problem of the aging fleet became better defined.

The Aloha accident may have contributed to recognition of the problem, but its symptoms have existed for some time. In 1983, an accident in a Far East Boeing 737 was attributed to fatigue cracks, and corrosion and multiple site damage (MSD) has been found on splices of Boeing and BAC aircraft and longerons of McDonnell Douglas aircraft. Many of the aircraft of the jet transport fleet are approaching or have already exceeded their design lives.

The scope of the aging aircraft problem may be seen from statistics shown in the following figures. Figure 1 shows the estimated age of aircraft in the fleet. (ATA Data). Figure 2 gives the distribution of cycles (takeoffs and landings) for two of the most popular aircraft in the fleet. Figure 3 gives the number of cycles estimated to be the design limit of each major aircraft in the fleet, and the number of flights the highest-time representative of that aircraft has achieved. As Aircraft age, it has become apparent that efficient maintenance programs based on analysis of aircraft structures will be necessary. Reliable inspection procedures would become the framework on which the life of the aging fleet would be extended.

It has rapidly become obvious that the need exists for improved NDI particularly in the following areas:

- Detection of crack growth as an element of fatigue damage to fuselage structures.
- Development of improved methodologies for characterizing integrity in bonded lap joints.
- Identification and isolation of corrosion damage in aircraft structures.
U.S. COMMERCIAL AIRLINE FLEET
Average Age: 12.7 Years

Fig. 1. Estimated age of the Commercial Airline Fleet

TOTAL AIRCRAFT: 3,671

Fig. 2. Distribution of flight time on DC-9 and 737 aircraft
Perhaps the major problem, however, is the huge scale of the task. As a result of FAA oversight of recent incidents, 849 Boeing 727's, 610 737's, and 195 747's are the subject of FAA Airworthiness Directives requiring periodic inspections. Current plans call for the individual inspection of thousands of fasteners and bonded joints on each aircraft; with current technology, the inspections of the existing fleet of some 1600 odd aircraft will require millions of dollars. Improved, more cost effective inspection methods are clearly needed.

![Graph](image)

**Fig. 3.** Comparison of design age with actual age of highest time aircraft in fleet

As a result of the recommendations resulting from the 1988 Conference, a research plan was completed in May, 1989, one component of which was a far reaching NDI initiative aimed at developing improved inspection methodologies for the air carrier fleet. The work includes an assessment of existing methods, a search for relevant methods not now being fully utilized, and an evaluation of emerging technology which might be brought to bear on the problem.

Oversight of the projects related to the initiative is obtained through an NDI Research Specialist who chairs the Aging Aircraft NDI Working Group (AANWG) which consists of representatives from the air carrier industry, aircraft manufacturers, academia, DOD and NASA. AANWG members possess knowledge of almost all of the NDI work ongoing in the industry and are competent to make judgments regarding its relevance to the nondestructive inspection requirements of the aging aircraft fleet. Individual members of the group provide their opinions to the FAA on new NDI initiatives, candidate sources of technology, training and certification, and other matters important to NDI of aging aircraft. Figure 4 shows the major elements of the NDI initiative.
The first task under the NDI initiative portion of the Aging Aircraft Program has been to assess the effect of baseline aircraft NDI activity, now being accomplished in two projects: first, ongoing audit of heavy maintenance checks, or "D" Checks, the major inspection carried out periodically by most commercial carriers to fulfill the FAA requirements for continuing airworthiness; second, a broad based survey of NDI practice, both in the aircraft industry and in other industries, which may have relevant technology.

**D-Checks**

Up to 60 heavy maintenance inspections are now being monitored by representatives of FAA engineering and inspection elements for uniformity of practice and effectiveness of procedures. The framework for this audit is provided by a massive checklist in which all elements of the inspection are covered from documentation to training and human factors. The NDI portion of the audit checklist seeks to determine types of inspections, procedures, instrumentation, training, qualification of inspectors, and storage and handling of specimens and samples. Data from the checklists are being collected, organized, and condensed with a view to preparation of a report late in 1990. Meanwhile, NDI data are being reviewed to determine uniformity and level of quality of the NDI practice, and to serve as a baseline for potential improvements to the system.

**Survey of NDI Practice**

The Nondestructive Testing Information Analysis Center is currently under contract to conduct a state of the art survey of NDI as related to its use in commercial aircraft over 7 years old. The purpose of the survey is to determine whether existing technology in other areas of the industry may be effective in improving the effectiveness of the inspection procedures now in use in the industry. The survey will contain, but not be limited to, the following elements:

1. Physical principles used, i.e. ultrasonics, eddy current, aided visual, etc.

2. Generalized description of the instrumentation. A listing of each instrument considered qualified for use, its specifications, approximate cost, and an estimate of the level of its acceptance by the industry, classified by physical principle from 1 above.

3. A generalized description of the inspection procedure used for each instrument cited in 2.
4. An assessment of the cost of the use of the instrument, either on the basis of cost per hour of use, or cost per inspectable unit or unit of area being inspected.

5. An assessment of the future development potential of the physical principle from 1, and some estimate of the ultimate limitation of the technique.

6. A summary evaluation of promising techniques from other areas, (DOD, nuclear, utilities, or others). This summary is heavily biased by considerations of the economic pressures found in the commercial aircraft industry.

7. A listing of sites on the aircraft where the bulk of the NDI is carried out, and the preferred instrumentation for these inspections.

A preliminary document is available now, and a final report is scheduled for August, 1990.

Workshops and Symposia

An important means for obtaining a continuing technology transfer between the NDI users and industry in general is through symposia and workshops. A series of workshops is being scheduled in 1990, beginning with one in April on Structures Fracture Mechanics; others are planned on Human Factors and Corrosion.

Other Activities

In addition to the above activities, a data base is being maintained of potential bidders in technical areas likely to become fruitful as new NDI initiatives. Those wishing to be on the bidders list will be requested to provide information about their capability and will be considered for projects in their areas of expertise. Also, a library of articles and up-to-date documents from current literature is being maintained and circulated. In addition to work with industry, Memoranda of Understanding are in effect or are being negotiated with elements of DOD and NASA.

MAINTENANCE INSPECTION AND REPAIR

In connection with its NDI responsibilities in the area of maintenance and repair, the FAA has several major tasks. The first task is evaluation of NDI equipment and procedures; supplementary work under this task is the organization and implementation of a comprehensive library of flaw samples. The second is to assess the NDI needs of the industry in engine NDI. The third task is to create guidelines for utilization of NDI practice by preparation of an FAA NDI Handbook.

The failure mechanism which led to the Aloha accident was known to exist considerably earlier. Figure 5 is a sketch of a Boeing 727 showing MSD in stringer 4, observed in a domestic flight in 1981. An Airworthiness Directive was issued as early as 1987 covering special inspections for the bonded lap joints used in some Boeing Aircraft.

Equipment Evaluation

Two major short term inspection problems exist within the aircraft fleet: the need to reliably inspect large numbers of rivets for the existence of multiple site damage (MSD), and the ability to inspect extensive areas of fuselage for adhesive bond integrity in the presence of corrosion and other contaminants. With industry help, various inspection methods are being evaluated in an effort to find the most reliable and cost effective method for inspection of lap joints and other sites in which MSD is likely to occur.
 Regina NO. N7286 (Line Position 342) - 1981
--Flight Hours Not Available
--Flight Cycles 39, 523

Figure 5. Sketch of damage observed on a Boeing 727 Aircraft in 1981

Figure 6, from the Boeing 737 NDT Manual, shows areas in a Boeing 737 which require emphasized inspection. Existing methods for detecting adhesive bonds are generally satisfactory in uncontaminated areas, but when corrosion, its byproducts, or other contamination exists in riveted lap joints and doubled butt joints, detection of adhesive bond integrity becomes unreliable. Accordingly, the FAA is diligently searching for a more effective method for inspecting the adhesive bonds in aircraft. From the data obtained, statistics may be derived for a given technique and compared with other competing techniques.

Criteria for Determining the Effectiveness of Inspection

The FAA is developing criteria for evaluating the effectiveness of NDI procedures. In general, these criteria are similar to those found in DOD and in airframe manufacturers' handbooks. They consist of utilizing a set of standard samples, some of which have characteristic flaws and some of which have no flaws. The samples are inspected by several inspectors, and the number of flaws detected are counted. The number of missed flaws is also counted (Class I errors) as well as the false positives (flaws averred to be present where no flaws exist re Class II errors).

Probability of Detection (PoD) is calculated for a given confidence level, as well as error rate and incidence of Class II errors. Figure 7 is a typical family of PoD curves for four commonly used NDI methods.

Table I is a listing, from Hagemaier1, of the common NDI methods and their capabilities and limitations.
<table>
<thead>
<tr>
<th>TYPE OF METHOD EMPLOYED</th>
<th>APPLICATION</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
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<tbody>
<tr>
<td>Visual Optical</td>
<td>Detection of surface defects or structural damage in all materials</td>
<td>Simple to use in areas where other methods are impractical; optical aids further enhance this method</td>
<td>Reliability depends upon the ability and experience of the user. Accessibility required for direct visibility or borescope</td>
</tr>
<tr>
<td>Penetrant</td>
<td>Detection of surface cracks in all metals, castings, forgings, machined parts, weldments</td>
<td>Simple to use. Accurate, fast, easy to interpret</td>
<td>Defect must be open to surface and accessible to operator. Defect may be covered by smeared metal. Part must be cleaned before and after check.</td>
</tr>
<tr>
<td>High Frequency Eddy Current</td>
<td>Detection of surface defects in metallic surfaces: cracks, pits, intergranular corrosion, and heat treat condition; conductivity for measurement for determining fire damaged area.</td>
<td>Useful for checking attachment holes for cracks not detectable by visual or penetrant methods. Fast, sensitive, portable.</td>
<td>Trained operator required. Sensitive to combinations and variations in material. Special probes required for each application. Reference standards required</td>
</tr>
<tr>
<td>Sonic</td>
<td>Detection of delaminations. Debonds. Voids and crushed core in composite and honeycomb materials</td>
<td>Can be accomplished from one surface. Direct reading. Does not require paint removal or special surface preparation</td>
<td>Loses sensitivity with increasing material thickness. Electrical source required</td>
</tr>
<tr>
<td>X-ray</td>
<td>Detection on internal flaws and defects such as cracks, corrosion, inclusions, and thickness variations</td>
<td>Eliminates many disassembly requirement. Has high sensitivity, and provides a permanent record on film</td>
<td>Radiation hazard. Trained operators and film processing equipment required. Crack plane must be nearly parallel to x-ray beam to be detected. Electrical source required. Special equipment required to position X-ray tube and film.</td>
</tr>
<tr>
<td>Magnetic Particle</td>
<td>Detection of surface or near surface defects in ferromagnetic materials of any shape or heat treat condition</td>
<td>Simple in principle, easy, portable, fast. Method is positive</td>
<td>Trained operator required. Parts must be cleaned before and demagnetized after check. Magnetic flux must be normal to plane of defect to yield indications.</td>
</tr>
<tr>
<td>Ultrasonics</td>
<td>Detection of surface and sub-surface defects, cracks, debonds, laminar flaws, and thickness gaging in most metals by pulse echo techniques</td>
<td>Fast, dependable, is easy to operate. Results are immediately known. Highly accurate, high sensitivity, and portable</td>
<td>Trained operator required. Electrical source required. Crack plane orientation must be known to select wave mode to be used. Test standards required to establish instrument sensitivity</td>
</tr>
</tbody>
</table>
Sample and Specimen Program

Samples and specimens play a large part in calibration, training, and development of procedures for utilizing NDI equipment on aircraft structures. Also, it is frequently necessary to evaluate fatigue by using complicated structures fully simulating the construction aspects and geometry of aircraft in which fatigue has been found. Accordingly, in order to meet the objectives of the Aging Aircraft Program, it is a vital requirement to collect and maintain a library of simple and complex examples representative of structures found on aircraft.

This library is now being assembled at the Department of Transportation's Transportation Systems Center in Cambridge, Mass. The specimens will be used to validate new NDI techniques, compare the effectiveness of instrumentation, quantify the effectiveness of various procedures and evaluate operator training.
Availability of specimens to those requiring them to promote research on aging aircraft will be on the basis of judgement by the FAA of the value of the research to the Aging Aircraft Program. If questions exist regarding the value of the research, a summary description of the research is sent to relevant members of the AANWG, and a decision is then made as to whether to prepare a specimen for the research initiative. Currently, a listing of specimens now in the inventory is available at the Transportation Systems Center.

Figure 8 is a Boeing sketch of the crack simulating fatigue found in some lap joints after extended fatigue cycles in service.

Fig. 7. Probability of Detection Curves for Common NDI Methods.

Fig. 8. Boeing sketch of a Specimen Simulating a Fatigue Crack in a Riveted Joint.
Figure 6 shows the configuration of both a Boeing lap joint and butt joint.

An approximation of the lap joint may be made up using Figures 6 and 8 with rivets on one inch centers.

Figure 9 from ATA Data shows the incidence of cracks and MSD in 727 aircraft. Large cracks are defined as 3 or more adjacent cracks or a single crack 10 inches or greater.

Most modern aircraft utilize both adhesive bonding as well as rivets to contain hoop stresses in the fuselage. Some early Boeing aircraft contained adhesive bonds which failed causing fatigue damage in the upper rivet rows of some lap joints. Just as important as detection of MSD in the rivet lines is the detection of bond integrity in both tear straps and lap joints.

Figure 10 from the Boeing 737 NDT Manual is a specification sheet which defines the adhesion specimen now used to detect bonding in the unriveted portions of the bonded doublers and tear straps. The inset shows the configuration of the bonded tear straps as well as the lap joints. No NDI method of detection of bond integrity beneath riveted joints is now accepted by Boeing.

Engine NDI

A study is now being conducted which will determine the rates of failure of various engine components and their impact on airworthiness. In addition, ongoing projects are aimed at the continued airworthiness of engine components. Current investigations include consideration of the effectiveness of magnetic particle crack detection methods, assessment of NDI on static components, and development of microsensors for early detection of flaws.
Fig. 10. Schematic details of Elements of Bonded Structure in Boeing 737 Airplanes.
NDI Handbook

Various elements of DOD maintained a handbook on NDI for many years, as has each of the air frame manufacturers. In an effort to provide guidance for minimum requirements for such a handbook, to be used by those certified by the FAA and to promote commonality of handbook approach, it is appropriate for the FAA to prepare a standardized FAA NDI handbook.

The FAA already has a NDI Advisory Circular, but it requires updating to be relevant to the needs of inspectors in the field. The current AC will be reviewed, along with other handbooks available from industry and DOD. When the review is complete, the FAA staff will prepare an outline for the FAA handbook and develop a plan for orderly flow of information on relevant NDI procedures into the handbook format. The deliverable from this work will be a series of recommended actions by the certifying authority in the FAA on best NDI practice for inclusion in the NDI handbook format.

NEW TECHNOLOGY

It is necessary for the FAA to concern itself with emerging technologies to keep pace with inspection tasks prompted by the rapid expansion of the aging fleet.

As promising techniques are uncovered, they are validated using tests and statistical principles described earlier. Probabilities of detection, confidence levels and false positives are estimated. Human factors considerations are factored into the statistical plan, and agencies within the FAA responsible for human factors are consulted for inputs to the experimental design. The new techniques are added to a matrix containing the types of flaws known to exist in air frames and the various technologies for detecting them. The whole is then incorporated in the NDI Handbook.

Resources have been allocated to evaluate new technologies using a series of contract efforts as well as studies on actual aircraft. At present, several initiatives are being considered:

- Development of a standardized method of sizing, characterizing and reporting flaws in aircraft structures.
- Evaluation of optimum eddy current procedures for inspecting lap joints.
- Development of improved image processing for x-ray photographs.
- Evaluation of on-board engine probes.
- Evaluation of the role of neutron radiography in detection of corrosion in aircraft structures.
- Eddy current imaging.
- Optical interference methods of large area microstrain measurement.
- Thermal diffusion measurement using infrared imaging.
- Acoustic emission in detection of incipient failure of critical structural elements.
- The role of x-ray diffraction in ndi of aircraft structures.

As resources become available within the FAA, other research initiatives will be evaluated and considered for inclusion on the program.
Pressure Test of 727 Aircraft

During manufacture, the fuselages of commercial airliners are pressure tested to the federally mandated 1.33 times the nominal pressure (P). Nominal pressure is conventionally assumed to be between 8 and 9 psi, depending on the altitude at which the aircraft flies. A real concern exists, supported by some evidence, that pressurization to 1.33 P in older aircraft may either introduce damage or accelerate the rate at which fatigue occurs in the structure, particularly if the proof pressure test (above 1.0 P) is to be carried out on a periodic basis.

To determine whether pressure testing is appropriate for older aircraft, the FAA will pressure test two 727 aircraft one with relatively few operating cycles, and one very high cycle aircraft.

Serious concerns have been raised in the technical community about the safety of the proof pressure test. Accordingly, another more viable pressurization approach has been proposed, namely pressurization to 1.0 P, with accompanying surveillance by relevant NDI methods to observe the progression of fatigue damage and identify its location.

Prior to pressurization, the aircraft will be subjected to an exhaustive and meticulous inspection, using the best of existing technology, including NDI. All damage or anomalous conditions will be rigorously and completely characterized and recorded.

Baseline Measurements -- Existing proven inspection equipment will be used in evaluation of the aircraft to provide baseline data about the aircraft condition. Two basic conditions will be evaluated: adhesive bond in the lap joints of the structure and evidence of cracks around rivet heads.

New Technology -- In addition to already validated technologies such as eddy current and bond testers, potentially valuable new technology will be utilized. Based on the hypothesis that any unrestored strains, when the structure is relaxed after pressurization, represent potential sites of stable crack growth, the NDI will focus on detection of crack growth during pressurization, evidence of non-linear expansion of the fuselage, and evidence of unrestored growth after depressurization.

Acoustic emission (AE) sensing may be able to detect the existence and location of all events of stable crack growth within the fuselage during pressurization.

Abnormal growth of sites on the fuselage as well as unrestored pressurization should be detectable, depending upon magnitude, by one of the methods below:

- Photogrametry (Accuracy ±0.010 inches)
- Moire Motion detection (Accuracy ±0.0001 inches)
- Shearograph (Accuracy ±0.000001 inches)

Each of the above is an area detection method covering large areas of fuselage during the pressurization cycle.

After pressurization, the aircraft under test will be carefully inspected for evidence of damage, and the data compared with those obtained prior to pressurization. The older aircraft will then be available as a testbed for validation of promising NDI procedures and new NDI technology.

REFERENCE