FAA Sponsored Nondestructive Inspection Research

David Galella, Thomas Flournoy, Federal Aviation Administration William J. Hughes Technical Center, Atlantic City Int'l Airport, NJ 08405

Abstract:

Timely and effective inspections are a necessary component for ensuring an aircraft's structural integrity. Since its inception in 1989, a major thrust of the FAA's National Aging Aircraft Research Program (NAARP) has been in the area of nondestructive inspection (NDI) with an initial focus on ensuring the reliable detection of cracks in large transport fuselage lap joints. Over the years, the program has evolved and matured and now encompasses almost all inspection related challenges needed to maintain the continued airworthiness of the entire commercial fleet. By this research, the FAA will develop, validate, and document inspection systems and practices with the ultimate goal of providing the aviation industry with improved systems and procedures that perform more sensitive and cost-effective inspections. Using these new or improved methods will reduce the number of inspection preventable failures and the associated loss of life and revenue that may accompany these failures.

To accomplish this goal, the FAA's Inspections Systems Research initiative is conducted largely at two major centers established to specifically support the inspection needs of the NAARP. The first, the Center for Systems Reliability (CASR), was established in 1990 at Iowa State University to develop new and innovative inspection methods to solve the unique inspection challenges facing commercial aviation. The second center, the Airworthiness Assurance NDI Validation Center (AANC), was established in 1991 for the FAA at the Albuquerque International Airport by Sandia National Laboratories. The mission of the AANC is to provide the FAA with the ability to conduct independent inspection and maintenance validation, reliability, and technology transfer activities that will help implement the improved practices into the industry.

Activities to date include studying and improving the most prevalent methods used today to inspect civil aircraft, namely, visual, penetrant, magnetic particle, ultrasonic, eddy current, and radiography. Other activities focus on the development and validation of innovative technologies such as those employing magneto optic imaging, pulsed eddy current, advanced

electromagnetic and ultrasonic sensing arrays, and, most recently, an exciting new technology called thermosonics.

This paper will provide an overview of the FAA's NDI research initiative, including its history, structure, some past research and validation accomplishments, and a look at the most promising technologies it is pursuing.

Introduction

With the catastrophic decompression of an Aloha Airlines airplane and the subsequent passage of the Aviation Safety Research Act of 1988, the Federal Aviation Administration (FAA) initiated a major effort to study structural integrity issues associated with the continued operation of the commercial aircraft fleet. Formally initiated in 1989, the National Aging Aircraft Research Program (NAARP) is managed at the FAA's William J. Hughes Technical Center in Atlantic City, NJ. Since its inception, the Inspection Systems Research initiative has been a significant element of the overall NAARP. Originally focused on large transport category aircraft, the Inspection Systems Research initiative has since evolved and expanded to include nondestructive inspection (NDI) research for the total airframe, including metal and composite components, and applications for both large and small transport aircraft, as well as rotorcraft.

This paper will describe some of the FAA's past and on-going efforts in NDI and serve as an update to previous overviews reported by Smith, et al.[1][2].

Program Goals

The intent of the FAA's Inspection Systems Research initiative is to develop, validate, and document inspection systems and practices that can enable the aviation industry to perform better inspections. The following measurable inspection performance goals represent a non-inclusive list identified by aviation industry experts and serves as guidance for the FAA's inspection activities. These goals include:

- Detection of 0.025-inch long cracks emanating from the shank of a counter sunk rivet hole in 40 mil fuselage skins
- Detection of 0.050-inch long cracks emanating from the shank of rivet holes in the second and third layers of aluminum fuselage skins (40-60 mills below surface)
- Detection of 0.100-inch long cracks under 0.500 inches of aluminum
- Detection and quantification of corrosion thinning of 5% material thickness loss
- Detection of one-half square inch disbonds in composites laminates up to 7 layers deep

Program Approach

To achieve these inspection goals, the FAA has chosen a two-prong approach that focuses equally on (1) the research and development of innovative inspection technologies and (2) the validation and technology transfer of the most promising NDI methods to the industry. It is along these lines that the FAA established two national NDI centers - each playing a distinct role in the advancement of NDI technology for aviation usage.

Center for Aviation Systems Reliability. The Center for Aviation Systems Reliability (CASR) is a university consortium founded by the FAA in response to the Aviation Safety Act of 1988. Established in 1990, the center serves as a focal point for the FAA's research and development of quantitative nondestructive inspection technologies for aircraft structures and materials. Iowa State was selected as CASR's lead university based on the broad technical competence gained by its Center for NDE through previous government sponsorship by the U.S. Air Force, National Science Foundation, National Institute of Standards and Technology, and Department of Energy. Other major CASR universities include Northwestern, Wayne State, and Ohio State. Together, these universities provide the FAA with a world-class applied research capability in the areas of radiography, penetrant, electromagnetics, ultrasound, thermal, and optical NDI methods.

Airworthiness Assurance Nondestructive Inspection Validation Center. The FAA established the Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) at Sandia National Laboratories in August 1991 under a governmental interagency agreement. Originally, the AANC's primary function was to support the FAA's NAARP by

conducting assessments of existing and emerging NDI technologies and facilitating the transfer of the most promising systems to industry. In recent years, the role of the AANC has broadened to cover almost all aspects of aircraft maintenance, inspection, and repair including projects involving large transport, commuter, rotorcraft, and to a lesser extent, general aviation aircraft.

To provide a realistic testing environment, the AANC leases a hangar on the west side of Albuquerque International Airport. The hangar houses 16,875 square feet of aircraft storage space; 7,762 square feet of office, conference, and laboratory space; and approximately 100,000 square feet of outdoor ramp space. Residing in the hangar are several decommissioned aircraft test-beds including a Boeing 747, a Boeing 737, a McDonnell Douglas DC-9, a Fairchild Metro SA-226, Bell TH-57 and UH-1 helicopters, and a Dassault Falcon from the Coast Guard. In addition to these aircraft, AANC maintains a structural specimen library containing hundreds of smaller specimens collected from retired aircraft. These specimens are used by AANC personnel for system validation efforts and are available to CASR and other independent system developers to assist them advance their maintenance and inspection technologies. Figure 1 shows a test-bed aircraft outside of the AANC hangar.

Figure 1. A Commuter NDI Test-Bed at the FAA's AANC Facility.

AANC has several NDI laboratories and state-of-the-art inspection systems including a fully functional liquid penetrant processing line, a thermography lab, scanning eddy current and ultrasonic imaging systems, and a magneto optic imager. In addition to these facilities, AANC is able to draw upon the substantial expertise and state-of-the-art facilities at Sandia National Labs.

Program Structure

In pursuing these goals, the FAA's Inspection Systems Research initiative maintains a broad research agenda that is currently organized under the following major task areas:

- NDI for Crack and Corrosion Detection
- NDI for Composites and Disbond Detection
- Visual Inspection Research
- Maintain AANC Infrastructure and Quick Response Capability

Following is a brief description of the current and planned activities related to each of the major task areas.

NDI for Crack and Corrosion Detection. Efforts to more ably detect cracks within the airframe take priority over all other task areas within FAA's Inspection Systems Research initiative. The objective is to improve the sensitivity and reliability of techniques to detect and characterize small surface and subsurface cracks characteristic of widespread fatigue damage. FAA sponsored crack detection technology development occurs mostly at CASR, but some research is also done using the Department of Transportation's Small Business Innovative Research (SBIR) Program.

In addition to technology development, this task area allows for validation studies of both advanced and traditional NDI methods to assess reliability and to determine where improvements can be accomplished. Crack detection validation efforts conducted to date include those which quantify the reliability to find cracks growing from fastener holes in surface layers and those in the second and third layers of aluminum lap splice joints using various technologies including sliding probe eddy current, MOI, pencil probe, self-nulling probes, and eddy current scanners. Future validations will focus on thicker multi-layer structures and bolt hole inspections.

A second effort under this task heading seeks to develop and apply new technologies to detect and characterize corrosion within lap joints and other hidden or inaccessible areas on aircraft. Most of the FAA sponsored systems under development use imaging capabilities

that can provide the inspector with an intuitive map showing areas of thinning metal. Many of these technologies are closely related to those named above for finding cracks and include thermal wave imaging, pulsed eddy current, magneto optic imaging, as well as other advanced electromagnetic and ultrasonic imaging methods.

Mature technologies are also validated at the AANC using a well-characterized set of corrosion lap joints panels designed and constructed for specifically for this purpose. The specimens represent realistic aircraft structure that contain various degrees of corrosion (varying in both area and thickness loss). Specimens include those containing engineered flaws, which simulate actual corrosion with strictly controlled characteristics, and those from real aircraft containing both natural and artificially-induced corrosion.

Although the NAARP initially focused on large transports, rotorcraft and commuter aircraft are now facing proposed damage tolerant rules (FAR Part 29.571 and NPRM 99-02) and they have similar fatigue and corrosion concerns. In this regard, NDI systems development of crack and corrosion technologies are generally done so as to have the broadest application to aluminum airframe aircraft including large transport, commuter, general aviation, and rotorcraft. System validation efforts are necessarily more focused and targeted for specific model aircraft and components. Tasks specifically addressing commuter and rotorcraft inspection issues are being conducted to assess the role conventional and advanced NDI techniques can play in solving these problems.

NDI for Composites and Disbond Detection. Technologies investigated as part of this task area will result in improved methods of determining the presence of disbonds in metal-to-metal, composite-to-metal, and all-composite bonded structures. Systems under development include a Computer Aided Tap Tester (CATT), advanced ultrasonic techniques, and thermal wave imaging. Figure 2 shows the CATT system developed by CASR researchers.

In addition to the technology development efforts, validation studies to determine the reliability of various existing and emerging methods to detect disbonds and delaminations in typical composite aircraft structures are being conducted. These efforts are done in collaboration with the SAE Commercial Aircraft Composite Repair Committee (CACRC) Inspection Task Group. The FAA previously worked with the CACRC to develop a set of

generic composite reference standards for use in calibrating NDI test equipment prior to conducting pre- and post-repair damage assessments. This minimal set of reference standards will ensure accurate and consistent inspection performance. Both composite laminate and composite honeycomb standards have been developed.

A task involving rotorcraft inspection focuses on damage tolerant flaw growth and detection within composite rotor hubs. Data collected from this task will prove useful for certification issues and with making improvements to the manufacturing, inspectability, serviceability, and cost-effectiveness of composite rotorcraft components.

Within this task area, efforts are also being conducted to validate improved methods of repairing metal aircraft using bonded composite doublers. The use of bonded composite doublers offers the airframe manufacturers and airline maintenance facilities a cost-effective technique to implement structural repairs or reinforcements of aging aircraft. In many cases these doublers are a more practical and robust alternative to using complex, mechanically fastened metal doublers. However, before this advanced aircraft repair technique can be accepted for commercial aircraft use, uncertainties surrounding the application, subsequent inspection, and long-term endurance of composite doublers need to be addressed. The objective of this task is to develop and test composite doubler technology for a select set of commercial aircraft applications. The results will generate information that supports FAA guidance regarding airworthiness compliance of composite doublers. Starting with an L-1011 door corner reinforcement effort completed in 1997, this on-going research at the AANC will develop a family of generic composite skin repairs for the DC-10/MD-11 aircraft that are fully validated. Figure 3 shows a composite patch repair on a DC-10 aircraft.

Finally, a task addressing adhesion and fatigue inspection issues related to retread aircraft tires is being conducted. This task will develop data to ensure safe aircraft tire re-treading limits.

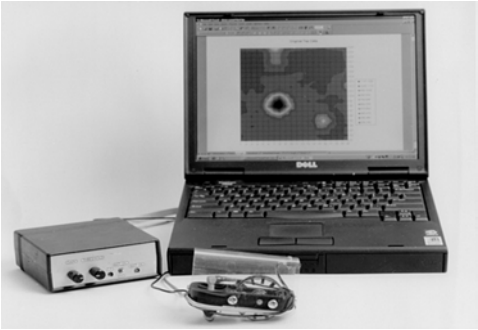

Figure 2. Prototype Computer Aided Tap Tester (CATT) showing C-Scan display results.

Figure 3. Born-Epoxy Composite Patch Shown Installed on a FedEx DC-10 Aircraft.

Visual Inspection Research. Visual inspection is the primary nondestructive method used to ensure the structural integrity of aircraft, accounting for an estimated 80 percent of the inspection workload for transport aircraft. Data collected from earlier efforts within this task area formed the basis for a visual inspection reliability benchmark. This benchmark was obtained from visual inspections conducted by actual airline inspectors on the AANC's Boeing 737 and Fairchild Metro test-beds. Results from these two experiments revealed a high degree of inspector-to-inspector variability for similar tasks and task-to-task variability for the same inspector. Based on video analysis of those experiments, it appears that the variability was due mostly to inadequacies in the inspector's search method (as opposed to his decision making). Armed with this knowledge, a significant study was initiated to determine how the information contained in the inspection job cards affects a visual inspector's performance. This on-going study called the Search Instruction Characterization Experiment required the support of 42 airline inspectors from several participating airlines.

From this experiment, it is anticipated that numerous other opportunities for further visual research studies will be identified. One such study will correlate results recorded by airline inspectors while at the AANC hangar facility to those obtained by the same inspectors at their home facilities. Another study would determine how crack morphology affects an inspector's ability to identify and decide on the disposition of an indication. Results from all these studies are expected to support the updating of an FAA advisory circular on visual inspection.

Maintain AANC Infrastructure and Quick Response Capability. In 1993, the AANC hangar was dedicated as a facility that could allow the FAA to conduct inspection validations on full-scale and well-characterized aircraft test specimens in a realistic

maintenance environment. Over the years, the validation capabilities and resources possessed by the AANC have proven themselves valuable to the FAA and aviation community. This task area maintains the AANC as a ready resource through which the agency can readily conduct necessary NDI and repair validations. This task provides the necessary funding to manage, staff, and operate the AANC on a continuing basis for the FAA. Funded activities cover the day-to-day management and operation of the AANC and the procurement of necessary equipment and aircraft test specimens to keep the AANC a viable and highly capable, maintenance, inspection and repair validation facility. In addition to infrastructure support, this task area also enables the AANC and CASR organizations to conduct quick response validation studies on pop-up inspection issues that frequently must be addressed by the FAA. These pop-ups may be the result of an aircraft accident, incident, or NTSB recommendation. The output of this task area is the stable, continued operation and readiness of the AANC and CASR to provide quick response NDI validations as requested by the FAA.

Past Successes

Over the past decade, the Inspections Systems Research initiative has conducted numerous activities that have produced dozens of useable products for both the FAA and industry. The following is a listing and brief description of the more significant successes of the program. This list is a sampling intended to illustrate the wide breadth of inspection related activities conducted over the years.

Technology Development Accomplishments

- Working together with the AANC, CASR researchers at Northwestern University successfully developed a prototype ultrasonic device that has been specified in a McDonnell Douglas Service Bulletin as an alternate inspection technique for a DC-9 wing box Tee-cap inspection (see figure 4). This inspection is safety critical and was mandated by FAA Airworthiness Directive. The new technique results in a more comprehensive and more sensitive inspection that can save over 700 man-hours per inspection compared to the current inspection method. It also requires less disassembly of the aircraft, resulting in less chance of ancillary damage. In July 1996, a major U.S. airline completed inspection of six DC-9 aircraft. During this

inspection, cracks were detected in the vertical flange of the wing spar tee by the new ultrasonic method that would not have been detected using the visual inspection (fuel tank entry) method. The cost savings to the airline on this inspection was estimated to be $283,000. The same technology has been used to inspect a DC-10 spar-cap/strap connection. A revised Supplemental Inspection Document for this inspection has also been published.

Figure 4. FAA Funded Ultrasonic Scanning System Applied to a DC-9 Tee-cap

- In 1997, major U.S. airlines expressed interest in CASR's Thermal Wave Imaging system for bond integrity verification and early corrosion detection. Northwest Airlines has asked Boeing to authorize the use of thermal wave imaging for both repetitive inspections and terminating actions as called for in service bulletins. United Airlines also asked Boeing to authorize the use of thermal wave imaging for similar inspection application. Boeing is taking steps to add thermal wave imaging as a generalized procedure to all Boeing NDI manuals.

- In 1999, a simple and reliable automated tap tester developed by CASR was licensed to a vendor of testing equipment. The hand-held tap tester used in conjunction with a notebook computer produces consistent quality scans of composite structure and its flaws. Two Computer Aided Tap Test systems have undergone beta-site testing at American Airlines. Other field tests have been conducted at Boeing, United Airlines, Northwest Airlines, and Midwest Express Airlines.

- In 1996, Iowa State University signed a licensing agreement with a manufacturer of inspection equipment for commercialization of a CASR-developed advanced, pulsed

eddy current inspection system. Boeing has already expressed interest in purchasing a unit. The advantage of the pulsed eddy current technique is in its wide bandwidth, which permits a single probe and a single measurement to provide information over a broad frequency range.

- CASR researchers at Iowa State University developed a prototype immersion-quality, focused ultrasonic inspection device built for use in the maintenance hangar. Known as the "Dripless Bubbler", the prototype was successfully tested in the laboratory and a field demonstration was conducted at Northwest Airlines. The commercially available device and its inventors were the recipients of R&D Magazine's 1996 R&D 100 Award.

- Building on a National Science Foundation initiative, CASR researchers at Iowa State University further developed an x-ray inspection simulator (XRSIM) with an advanced graphical user interface. The software's intended uses include 1) the optimization of x-ray inspection procedures, 2) parametric studies for sensitivity and reliability analysis, 3) verification of inspectability claims, and 4) inspector training. In 1992, an early version of this software was used to validate a DC-9 rear bulkhead inspection. McDonnell Douglas personnel reported excellent agreement with experimental results.

- CASR researchers at Northwestern University developed an advanced optical inspection technique, called Additive-Subtractive Phase-Modulated Speckle Interferometry (ASPM-SI), which reduces the effects of the noise on the interferometric images. In 1993, a commercial supplier of shearography systems, Laser Technology, Inc. (LTI), entered into a licensing agreement to integrate this new technology into their products.

- Under FAA sponsorship, researchers at Penn State developed a unique guided wave ultrasonic inspection system for aircraft fuselage lap joints. Results of this effort indicated that such ultrasonic waves could identify disbonds similar to those that contributed to the 1988 Aloha accident. Although proven technically successful, this technology was not commercially successful because of its limited number of

applications and small anticipated market. In 1997, Discover Magazine recognized the principal researcher with its finalist award for innovative technology research.

- A prototype D-Sight Inspection System was developed collaboratively with funding from the FAA, Transport Canada, and the U.S. Air Force to better detect surface defects including skin pillowing due to the effects of corrosion. The Canadian Department of National Defense and the U.S. Air Force have purchased versions of the system for testing at their maintenance depots. As a by-product of this work, FAA-funded researchers at the Canadian National Research Council identified a potentially serious crack initiation mechanism due to local stresses caused by corrosion pillowing.

Validation and Technology Transfer Accomplishments

- The reliability of eddy-current inspections of lap joints was quantitatively assessed in actual maintenance facilities. Nine maintenance facilities performed an eddy-current inspection on calibrated reference panels to determine probability of human error under field conditions. Results were documented in a FAA technical report in 1995. This study established a consistent and systematic methodology to assess the reliability of nondestructive inspections through field experiments.

- In September 2000, researchers at the AANC generated probability of detection (POD) data for typical second- and third-layer crack inspection procedures that demonstrated that the assumed POD at the targeted crack size was inaccurate. Analysis of the data indicated that there were several probable causes for the inaccuracy. These results have been used to update existing procedures, and will ensure the adequacy of similar procedures yet to be issued.

- In 1997, the AANC completed a Small Crack Structured Experiment which concluded that several emerging electromagnetic techniques including NASA's self-nulling eddy current probe and Northrop's Low Frequency Eddy Current Array, could reliably detect cracks before growing beyond the head of the fastener.

- In 1996, the AANC completed a benchmark visual inspection reliability experiment which examined industry-accepted assumptions regarding overall visual inspection reliability and the factors which affect visual inspection. Twelve airline inspectors performed typical visual inspection tasks on the AANC B-737 and on fabricated small crack panels. The data from this experiment shows a high inspector-to-inspector variability in performance that is now the subject of follow-on Visual Inspection research.

- An Advisory Circular on Visual Inspection of Aircraft was produced for the FAA's Flight Standards Service in 1996.

- In 1997, the AANC worked with Delta Air Lines and Lockheed to install the first bonded composite doubler on a commercial aircraft. While this is primarily a repair issue, NDI methods to perform the necessary surveillance of the doubler were developed. A C-scan ultrasonic inspection of the doubler was validated and the FAA issued an Alternate Means of Compliance to apply this inspection technique to an L-1011 door corner repair. The AANC-developed inspection procedures are now part of the Lockheed Service Bulletin 093-53-278 for all L-1011 aircraft.

- Since July 2000, AANC worked with FedEx and Boeing personnel to install composite doubler repairs on seven of their DC-10 aircraft. These installations were the first time bonded composite doublers were used as permanent repairs for skin damage of a commercial aircraft operated in the U.S. Data collected from this research will provide a basis for the FAA to draft advisory material on the proper use of composite repair patches.

- A fully functional liquid penetrant evaluation facility was established within the AANC hangar facility. In 1997, with the cooperation of U.S. Air Force personnel and a well-characterized set of cracked specimens, this facility demonstrated a capability similar to the penetrant qualification facility at Wright Patterson AFB. This capability will allow the AANC to maintain and enhance the evaluation of penetrant inspection materials and the evaluation of emerging penetrant materials, processes, and technology.

- As a follow-on to a U.S. Air Force effort, the FAA had the Nondestructive Testing Information Analysis Center collect, synthesize, and compile existing inspection capability and reliability data into an Nondestructive Evaluation (NDE) Capabilities Data Book. The NDE Capabilities Data Book provides an engineering reference for use during NDE engineering analyses and for development and validation of new NDE procedures. Probability of detection reference data in the Data Book can be used to select an NDE procedure for a specific application and for assessing the relative merits of alternative NDE procedures. The second edition, which contains over 400 data sets, was published in 1997 in both hard copy and CD-ROM formats.

- In January 1995, the Federal Register announced a revised Airworthiness Directive, AD 93-21-12, that allows an alternate AANC-developed inspection procedure for finding corrosion in the wing attachment of Piper PA-25 aircraft. The inspection procedure made use of a portable, ultrasonic thickness gauge. It also demonstrated the program's ability to impact general aviation applications.

- The AANC conducted a series of experiments to develop the best sorting method to determine the metal alloys that make up the engine exhaust parts of a Cessna 400 series aircraft prior to conducting a mandated crack inspection. This study was by spurred by an accident and subsequent NTSB recommendation to the FAA to update Advisory Circular 65-9A, Airframe & Powerplant Mechanics General Handbook. The AANC delivered a final report to the Airworthiness Programs Office, AFS-610 in February 1998.

- In October 2000, two Aerospace Recommended Practice (ARP) documents developed by the AANC with assistance from the Commercial Aircraft Composite Repair Committee (CACRC) were published by SAE. ARPs 5605 and 5606 describe how to fabricate sets of composite honeycomb and solid laminate reference standards that can be used by the operators when conducting pre- and post-repair inspections. Widespread use of these standards is occurring as airframe OEMs reference them in their NDI Manuals.

- An Acoustic Emission Halon Bottle Tester was developed and in December 1997 was approved by the DOT for use by ATA airlines. The tester ensures the integrity of the spherical Halon bottles without the need for the costly hydrostatic test which requires the removal and capture of the Halon. Versions of this prototype are now used regularly within the aviation industry. Figure 5 shows the prototype acoustic emission tester.

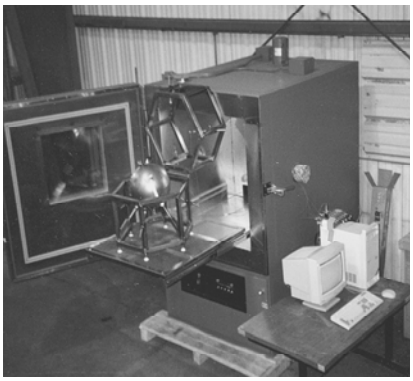

Figure 5. Prototype Acoustic Emission Tester for Halon Bottles.

- In September 2000, AANC developed a dual-frequency eddy-current technique for detecting corrosion in thin aluminum skins used in rotorcraft. A field validation study was conducted and Bell Helicopter will incorporate the method into its NDI manuals.

Promising Technologies

The FAA is currently funding the development and validation of several promising NDI technologies. This section highlights four such technologies and describes briefly their principles of operation, capabilities, and future applications. Further details on the following can be found in a draft summary report compiled by Smith, Galella, Brasche, et al.[3].

Scanning Pulsed Eddy Current (SPEC) A novel eddy-current application called Scanning Pulsed Eddy Current (SPEC) was developed at CASR by the late John Moulder [4]. SPEC utilizes a pulsed excitation to drive the probes as opposed to conventional eddy-current systems that use time-harmonic excitation. The advantages of pulse excitation lies in its broadband nature as a spectrum of eddy-current frequencies are applied simultaneously to the test specimen. Unlike multi-frequency eddy-current techniques, the information is contained in a single time-domain signal, which is analogous to an ultrasonic pulse-echo signal modified by the laws of diffusion. For example, the time at which certain features appear in the signals can be approximately related to the depth of the flaw from which they originated, and, more importantly, this information can be used quantitatively [5].

A second-generation SPEC system has been developed under FAA funding with the goal being to eventually transfer the technology to the airlines. Currently, a laboratory prototype system is fully functioning and is being used for demonstration purposes and to evaluate performance. Two field systems were constructed for further beta-site testing in January 2001. The second-generation laboratory SPEC system was completed in the spring of 2000 and features a number of significant enhancements over the previous system.

One of the main innovations used was a current-drive circuit instead of a voltage drive circuit. The new current drive precisely controls coil current such that it has an exponentially rising and falling form. This allows the coil field to trace the same shape, as it is proportional to the current. In addition, the unit uses Hall-device sensors which offer improved low-frequency performance and hence greater penetration [6]. The combination of Hall-element sensors and current-drive capability allows the implementation of an effective temperature compensation algorithm that solves all the temperature stability problems previously encountered. Algorithms have also been developed that eliminate the effects of edge signals. Figure 6 shows the second-generation system.

Figure 6. Laboratory version of the second-generation SPEC system showing scanner and C-scan output display.

Results obtained to date, using an induction probe easily demonstrated the ability to detect 0.060-inch milled slots in the second layer of a lap joint [7]. These results were not obtained under optimal conditions; therefore, it is likely that performance could be further improved if a specific problem or geometry was targeted. The second-generation laboratory system has been working well for some months and is capable of being used in the field. However, the

system is a little cumbersome and requires some degree of skill to setup. For this reason, the researchers are working on two field systems, the first of which will be delivered to Boeing, Seattle. Boeing participated in an evaluation of the first-generation prototype system which resulted in the improvements seen in the second-generation system.

In 2001, the FAA initiated a project at the AANC to validate and transfer pulsed eddy current technology to the field. The effort involves working with CASR and other competing pulsed eddy current researchers to first identify the most mature pulsed eddy current system and then apply it to a thick, multilayered, commercial aircraft application, such as the DC-10 crown splice joint. This project will result in a validated procedure that would allow the first practical and widespread use of pulsed eddy current technology. Research efforts will also be conducted to optimize the Hall probes used during pulsed eddy current scanning.

Magneto Optic Imaging (MOI) Currently, there are more than 70 MOI devices used to inspect in-service aircraft at various airlines, OEMs, maintenance, and military establishments throughout the world. Magneto optic imaging allows instantaneous imaging of surface eddy currents induced in the article being inspected. Although the eddy-current response measurement at any specific point may be no more sensitive than what might be done by a point-measurement probe, the MOI takes full advantage of the inspector's ability to interpret visual images. This can significantly increase the sensitivity of the inspection when compared to an inspection based solely on the point-by-point exceedance of a determined threshold.

The magneto optic sensor images the normal components of the magnetic field induced in the test article by an induction planar foil carrying alternating current. Presence of defects perturbs the flow of eddy currents resulting in the generation of normal magnetic fields. When a linearly polarized light is projected on a magneto optic sensor that is placed on top of the foil, the normal magnetic field rotates the plane of polarization. In practice, the MOI uses this principle but with a sophisticated foil excitation that results in more complete and more intuitive images of the inspection article and its flaws. An example of a typical MOI display and system are shown in figures 7 and 8, respectively.

The probability of detection (POD) curves shown in figure 9 were obtained at the AANC using the MOI on a set of fatigue crack samples produced to evaluate various inspection

techniques. The four curves to the right were obtained using the earlier MOI 301 and eddy current-based sliding probe. The furthest curve on the left was obtained using the newer MOI 303 and shows how performance has improved due in part to upgrades funded by the FAA as a Phase 2 SBIR project.

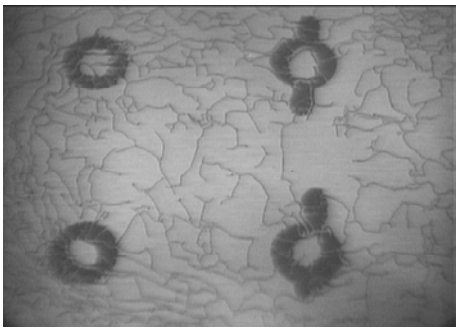

Figure 7. A typical MOI display showing actual fatigue cracks. The two rivets at the left have no defects while the two at the right show cracks emanating from the top and bottom.

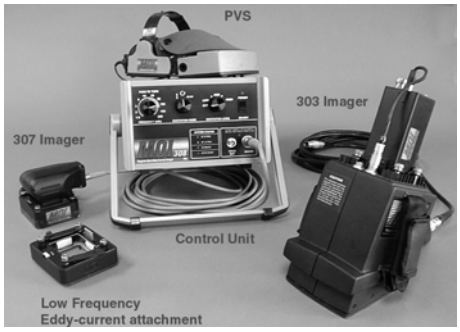

Figure 8. Photograph of MOI Model 307 which was developed with FAA SBIR funding.

Experience in the field has determined that certain defects under rivet heads can be detected due to anomalies in the field distribution and consequent distortions in the MOI images. One example is circumferential cracks under rivet heads in dimpled countersinks.

Magneto optic images provide a qualitative estimate of the size of the defect that it detects. Interpretation of images could be aided by numerical computations. Numerical models simulating the magneto optic phenomenon, funded by the FAA at the CASR, are being used to determine quantitative values of the fields under various parametric conditions. Results of this study are being used in predicting the capability of the imager and improvements needed in the sensor for specific applications.

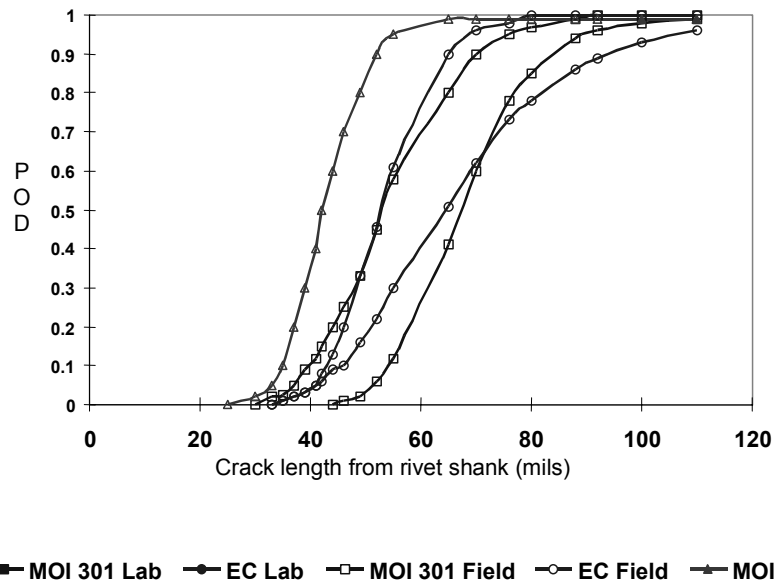

Figure 9. POD curves for various versions of the MOI vs. the Sliding Eddy Current Probe (EC).

Fundamental improvements of the instrument's magneto optic sensor are also being funded by the FAA. To detect smaller cracks, CASR and PRI Research and Development Corp. investigators are using the parametric studies noted above to predict and then formulate a more sensitive sensor. The simulation models are used to visualize the magnetic field distribution produced by anomalies and to determine the quantitative values of the fields generated by these anomalies. Using automated defect detection tools will also permit greater consistency and reliability in the detection process. Such developments will require approximately two years to implement.

Thermosonics This technology, patented in 2001 by Wayne State University as a member of CASR, offers both a broad area inspection capability and a high sensitivity method to detect surface and near-surface breaking cracks and other defects. Thermosonics locates fatigue cracks in structures by imaging the thermal signature of crack interfaces as they heat up when exposed to sound energy. In this method, a short (50ms to 500ms) pulse of high power (300w to 800w) sound/ultrasound (20 kHz) is injected into the part. The sound causes the crack faces to rub together, which in turn, causes local heating of the crack faces that can be detected by an infrared (IR) video camera. It is a dark-field method in which the heat from the rubbing crack surface appears as bright features against a dark background. Figure 10 shows a thermosonic image of a crack in the area of a bolt hole on a DC-10 nose

wheel. The infrared image on the left shows no visible cracks at the bolt hole prior to sonic excitation. During ensonification of the same hole, the infrared image at the right clearly shows radial cracks at the 6 and 9 o'clock positions and a circumferential crack between these points. Although evident in this image, the crack indication is even more obvious when viewed dynamically at the time of ensonification.

As it has been only 2 years since this new NDI method was invented, thermosonic crack detection is best described as a laboratory method having excellent potential to be applied in the field. A lab bench commercial product is already available through Indigo Systems, Inc., Santa Barbara, CA, as a licensee of the patent. To date, both surface and subsurface cracks have been detected in a variety of metals (aluminum alloys, steel, and titanium), including cracks beneath thermal barrier layers. Cracks in aircraft structures have been detected as noted previously by the DC-10 nose wheel example and by the detection of a crack in a section removed from a DC-9 tee-cap as shown in figure 11. In this image, the crack is detected as breaking the surface on one side and as a subsurface crack on the other.

Although the technique has clearly demonstrated its ability to detect cracks, the relationship between crack characteristics (length, tightness, depth, etc.), material, external factors (e.g., contamination), and indication level is not yet well understood. Immediate efforts by the FAA are being undertaken to better understand the thermosonic phenomena.

In addition to metals, cracks (in the form of delaminations and disbonds) have been detected in polymer composites, along with regions of variable bond strength and cracks in brittle materials such as ceramics.

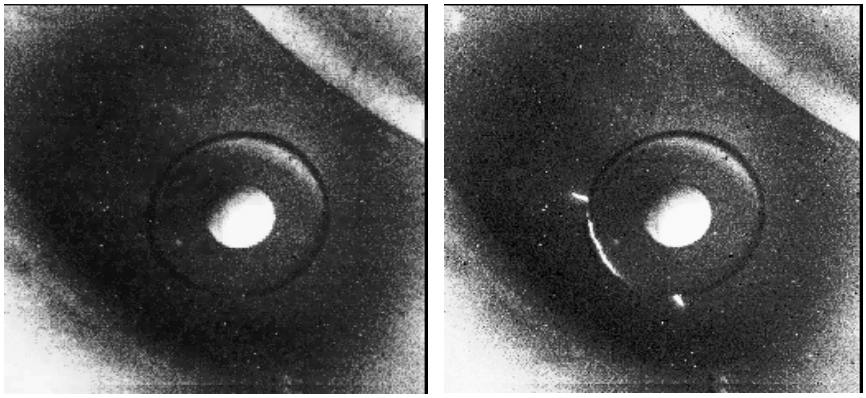

Figure 10. Inspection of an aircraft wheel using thermosonics. Left image shows wheel before ensonfication and right shows during ensonification with cracks appearing white at the 6 and 9 o'clock positions.

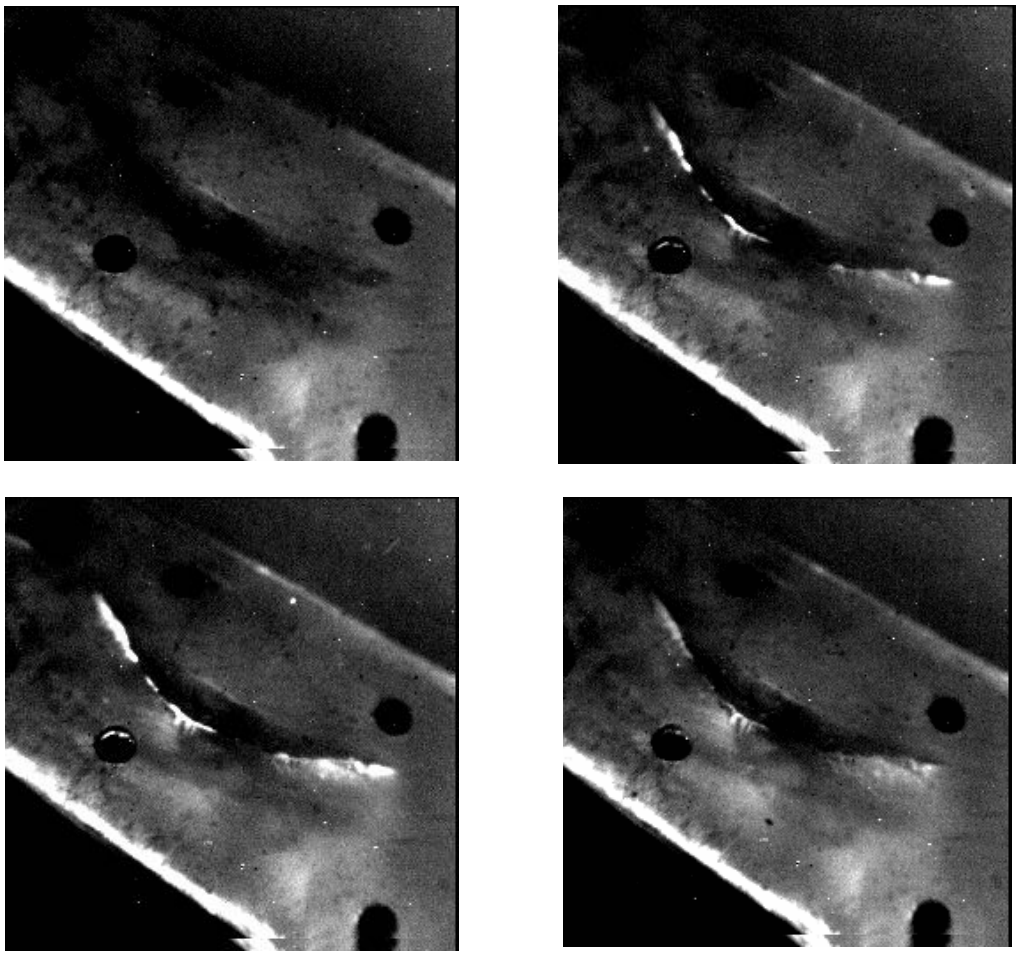

Figure 11. Selected frames from a thermosonic sequence of images of a DC-9 tee-cap taken before the sound pulse was applied (top left), just after the initiation of the pulse (top right), during the pulse (bottom left), and finally, just after the pulse was turned off (bottom right). A crack in the structure glows white while viewed by the infrared camera during ensonification.

Jentek's MWM™ With its Meandering Winding Magnetometer (MWM™), Jentek Sensors, Inc. has developed a novel eddy-current technology that provides significantly improved measurement precision of local material properties. By precisely measuring conductivity and magnetic permeability, the MWM™ eddy current instrument can detect early signs of fatigue damage, changes in residual stress, surface hardness, and case depth [8].

The Jentek MWM™ technology was first applied to characterization of widespread fatigue damage (WFD) as part of a Phase I SBIR for the FAA in 1995. The Phase I program

demonstrated the capability to detect clusters of microcracks in bending fatigue specimens. Detected cracks on typical specimens were on the order of 0.0005 to 0.0015 inch deep and were verified by destructive testing. The Phase I program also demonstrated evidence that these clusters of microcracks, referred to as distributed fatigue damage, also appear to exist on the Boeing 737 aircraft located at the FAA's AANC (this has not been verified destructively). Jentek further demonstrated the capability to distinguish between plastic deformation, associated with assembly near the floorboard region of this B-737 fuselage skin, and apparent fatigue damage from complex bending loads near the lap joint fasteners in the window skin panels. This damage occurred as far as 6 inches from the fasteners and was correlated with the positions of macrocracks that had been detected at the fasteners. Thus, the demonstrated capability to map distributed microcracking for microcracks smaller than 2 mils provides a potential to detect the onset of WFD for some structures. After the Phase I SBIR, the project was redirected during the years of 1996-2000 in order to fully focus the MWM™ on detection of cracks in engine disks.

Recently, Jentek has completed a new parallel architecture impedance instrument product, with proprietary scalable design, modular probe electronics, and high-resolution MWM™-array sensor tips. This product was designed specifically for detection of subsurface anomalies such as second- and third-layer cracks, hidden corrosion, and inclusions. One specific application currently being addressed by the FAA is detection of third-layer cracks in lap joints. The unique advantages of this new technology include (1) rapid parallel architecture scanning/imaging, (2) multiple frequency, absolute property imaging with potential to correct for variations in fastener materials, Alclad coating thickness, temperature, and skin thickness, and (3) conformable sensors for scanning of complex curvatures. Applying this new technology to the high profile problem of detecting discrete macrocracks under fastener heads will be addressed over the next year; however, the current focus is on detection of larger third-layer cracks (approximately 0.120 inch) and hidden corrosion/corrosion fatigue mapping.

The FAA is also following Jentek's development of a new surface-mountable eddy-current sensor technology. The new MWM™-rosettes, as shown in figure 12, would be mounted in between skins or on the inside of other hard to inspect, crack-prone areas. Very thin cables would extend out to a convenient location allowing frequent querying of the sensors. For

example, detection of second- and third-layer cracks may be easier from the inside surface in some applications but would be cost prohibitive if interior removal was required, as on older aircraft. Sensors could be installed on the interior surface or under repair doublers to permit detection of small cracks without future disassembly. In the lab, Jentek has demonstrated the capability to detect cracks smaller than 0.002 inch long in continuously monitored fatigue tests with surface-mounted MWM™-arrays.

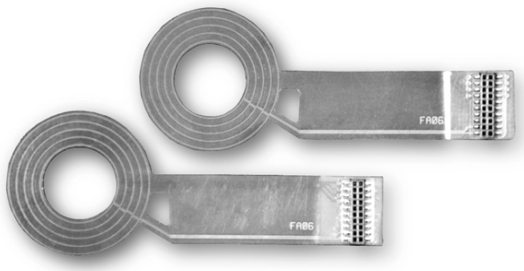

Figure 12. Photograph of the MWM™-rosettes.

Upcoming demonstrations with the new MWM™-rosettes for the U.S. Air Force, U.S. Navy and Lockheed Martin are expected to demonstrate detection capability limited only by the ability to locate the array over the crack site. It has been demonstrated that a crack can be detected as soon as it enters the sensor footprint, making detection of cracks smaller than 0.01 inches realistic for many applications that are currently limited to detection of cracks well over 0.05 inch long. The FAA is considering funding similar applications in 2003 on commercial aircraft by inserting such sensors under repairs, between skins of lap joints, in fuel tanks, or other interior surfaces for early detection of cracks.

Concluding Remarks

Since 1989, the Federal Aviation Administration has been conducting nondestructive inspection (NDI) research as part of the National Aging Aircraft Research Program. Although originally focused on large transport aluminum inspection issues, the Inspection Systems Research initiative has broadened to encompass maintenance and inspection activities across all sectors of civil aviation. This paper has briefly explained the history, goals, and organization guiding the research. Throughout the program, the FAA and its researchers at the Center for Aviation Systems Reliability and the Airworthiness Assurance NDI Validation Center, have worked closely with the industry and other governmental agencies to coordinate and facilitate the successful adoption of the various inspection products described here within. The FAA looks forward to furthering these collaborations as new inspection challenges arise that threaten the continued airworthiness of the aging commercial fleet.

References

1. Christopher Smith, "FAA NDI Research and Results Since the Aloha Incident," American Society of Nondestructive Testing Spring Conference and 7th Annual Research Symposium, March 23-27, 1998.

2. Christopher Smith and Patrick Walter, "Revisiting the Aging Aircraft Nondestructive Inspection Validation Center – A Resource for the FAA and Industry," Materials Evaluation, August 1995.

3. Christopher Smith, Dave Galella, Lisa Brasche, et al., "State of FAA Funded NDI Research for Application to Aircraft Widespread Fatigue Damage," draft report 2001.

4. R. E. Beissner, J. H. Rose, and N. Nakagawa, "Pulsed Eddy Current Method: An Overview," in *Reviews of Progress in Quantitative NDE*, Vol. 18A, eds. D. O. Thompson and D. E. Chimenti (Plenum Press, New York), pp. 469-475, 1999.

5. C. C. Tai, J. H. Rose, and J. C. Moulder, "Thickness and Conductivity of Metallic Layers From Pulsed Eddy Current Measurements," *Rev. Sci. Instrum*., Vol. 67, pp. 3965, 1996.

6. W. W. Ward and J. C. Moulder, "Low Frequency, Pulsed Eddy Currents for Deep Penetration," in *Review of Progress in Quantitative NDE*, Vol. 17A, eds. D. O. Thompson and D. E. Chimenti, (Plenum Press, New York), pp. 291-298, 1998.

7. J. A. Bieber, S. K. Shaligram, J. H. Rose, and J. C. Moulder, "Time-Gating of Pulsed Eddy Current Signals for Defect Characterization and Discrimination in Aircraft Lap Joints," *Review of Progress in Quantitative Nondestructive Evaluation,* Vol. 16B, eds. D. O. Thompson and D. E. Chimenti (Plenum Press, New York), pp. 1915-1921, 1997.

8. Neil J. Goldfine, Darrell Schlicker, Karen Walrath, Andrew Washabaugh, and Vladimir Zilberstein, "Application of MWM-Array Eddy Current Sensors to Corrosion Mapping," 4th International Aircraft Corrosion Workshop, August 22-25, 2000.