Trends in R&D for Nondestructive Evaluation of In-Service Aircraft

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Boeing In-Service Customers

- 777
- B-52
- F-22
- V-22
- 787
- F-18E/F
- KC-135
Challenges for In-service NDE

- Disbonds
- Cracks
- Moisture in Honeycomb
- Repair inspection
- Widespread Fatigue Damage
- Material Degradation
- Corrosion
In-Service NDE is Needed

New NDE technology is necessary to...
- Improve current detection capabilities
- Meet existing inspection challenges
- Address future NDI requirements

As Aerospace Systems age...
- More NDI inspections are necessary for continued, safe use
- Significant reductions in inspection time are required to minimize maintenance downtime for expensive assets
In-Service NDE Goals

- Reduce inspection time
- Reduce inspection costs
- Increase aircraft availability
- Reduce cycle time
- Increase repair options
- Increase inspection reliability / safety
Composite NDE
Composites Are the Smart Choice for Aircraft

<table>
<thead>
<tr>
<th>Passenger Benefits</th>
<th>Airline Benefits</th>
<th>Design Benefits</th>
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</table>
| • More comfort features  
  – Lower cabin altitude  
  – Increased cabin humidity  
  – Bigger windows | • Fatigue and corrosion resistant  
  – Reduced maintenance costs  
  – Fewer and easier inspections | • Conducive to larger, more integrated designs |
| • Reduced weight  
  – Lower fuel usage  
  – Lower landing fees | • Longer life; lower amortization costs | |

**Production Benefits**

- Fewer parts
- Improved quality
- Reduced flow times
The 787 Dreamliner is 50% Composite

- Composites: 50%
- Aluminum: 20%
- Titanium: 15%
- Steel: 10%
- Other: 5%
- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum/steel/titanium pylons
When is NDE Needed with Composites?

- Fundamental Studies
- Manufacturing Development Support
- Structural Test Support
- In-Process Measurement
- Production NDI
- Unplanned Event NDI
- Post-Production NDI (field, depot, PM)
- Damage Assessment & Repair NDI
- SHM Interface/Follow-up
Typical In-Service Damage in Composites or Composite Repairs

- Delaminations
- Disbonds
- Cracking
- Moisture Ingress
- Heat Damage
- Porosity
- Wrinkles
- Foreign Material/Objects

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Common NDE Methods Applicable to In-Service Composites

- Visual Inspection
- Tap Testing
- Ultrasonics
- Radiography
- IR Thermography
Current Challenges for In-Service NDE of Composites

• The Need for Speed
• Keep It Simple
• Increased Complexity of Structures
• Availability of Trained Inspectors
• Composite Repair Verification
• Degradation Quantification
Current Composite NDE Trends

- Inspection Speed
- Simplicity
- Quantification
- Large Areas
Automated Scanners and Linear Arrays

• Platform for one-sided inspection
• High scan rates
• NDI techniques include pulse echo UT, UT resonance and eddy current
• All data is stored digitally and electronically transferable
MAUS Scan of an Impact
Impact Damage imaged using UT time-of-flight C-scan.
Ultrasonic Pulse-Echo Image of a Repair

Composite Repair Patch with Inserts
IR Thermography for Disbonds & Water Ingress
IR Snapshots at Different Times
IRT, using RF Inductive Heating

- Inspection of Hat - Stiffener

- Inspection of structures that were hit by simulated lighting
Ramp Damage Checker

Description:
- A simplified pulse-echo instrument for use by personnel with no specialized training
- Simple “red light” / “green light” display
- Memorizes good structure (green LED), then looks for changes (red LED)
- Operates like a stud finder

Benefit to User:
- Facilitates dispatch decision at loading ramp
- Can be used by local maintenance people
- Determines if damage requires repair, ferry flight, or no action at all
Rapid Image-Based NDE

Imperium Acoustocam
Rapid Image-Based NDE

Example: Ultrasonic Flexible Array System (Sonoflex)
Rapid Image-Based NDE

**X-ray Backscatter**

- X-ray backscatter can be collected from one side
- Much lower radiation exposure than conventional X-ray
- Proven for use in Homeland Security

![Image of X-ray equipment and motorcycle X-ray]

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X-ray Backscatter NDE of Substructure
Water Intrusion Testing Comparison

Water Ingress Panel, with Potting

High Thermal Transient Infrared Results

X-ray Backscatter Results
Techniques currently available:
- Laser-induced fluorescence
- Raman Spectroscopy
- NMR
- Thermo-elastic characterization
- FTIR
Near IR for Thermal Damage Assessment

- Self-contained hand-held near IR spectroscopy system
- Near surface thermal damage quantification.
Near IR Inspection

System reading lightning strike subsurface damage
Near IR for Thermal Damage Assessment

Damage area measurement with near IR for lightening strikes

- Black dots are severe damage
- Orange dots are steadily decreasing damage
- Green dots are no apparent damage
Repair Strength-to-Defect Correlation

Deterministic NDE/SHM empirical-analytical ‘engine’

NDE/SHM Data

Structure of interest

Finite Element Analysis

Strength Tests

Increasing Return on Proper Part Disposition

Disbond

Sensitivity Situation

Disbond Nominal Situation

Disbond Tolerant Situation

Strength Reduction

Indication Parameter Magnitude (i.e. Disbond Size)

Very little disbond effect allowed before properties drop off.

Increasing Return on Proper Part Disposition

More disbond effect allowed before properties drop off.

Very little disbond effect allowed before properties drop off.

Deterministic NDE Predictions and Recommendations Available in IRET

- Stress/Strain, MoS
- Pass/Fail/Monitor

A Eddy current inspection is needed to determine if there is any corrosion. (Show Me How) Please report your findings below:

Deterministic NDE/SHM Predictions and Recommendations Available in IRET

- Stress/Strain, MoS
- Pass/Fail/Monitor
Remote Expert NDE
Problem

With the increase in composite structure in the world's commercial fleets, there will be many more incidents where possible damage needs to be inspected.

- Many NDE inspections on In-service aircraft are in response to a known issue and are of critical importance.
- There are other situations where there is just a suspicion that there may be a problem.
- In these cases an NDE expert will be dispatched to do a detailed, sophisticated, analysis of the situation.
- It can be expensive and time consuming to dispatch a certified NDE inspector to a remote location to do a survey of a known or suspected problem.
Remote Expert NDE

- Use modern wireless technology to allow an NDE expert to remotely monitor and control an inspection carried out by local, technically able but “non NDE expert” personnel.
Remote Expert NDE

NDE Data, Audio, Video of Inspection

Audio, Control of NDE Instrument
The keys to making a wireless, remote NDE inspection work are:

- Reliable wireless connection
- NDE instrument that can be controlled and viewed remotely.
- Remote NDE expert available
- Means to provide situational awareness to the remote NDE expert
Remote Expert End Effector Example

Acoustocam NDE instrument from Imperium was used in a Remote NDE Demonstration

Key Features that make it suitable for Remote NDE:

• Portable
• Live Imaging
• Computer controlled
• Wireless Connectivity
Digital Acoustic Video (DAVTM): Imaging Array

- Custom design
- $120 \times 120 = 14,400$ elements
- Piezoelectric material deposited
Acoustocam Ultrasonic Camera

- Source transducer
- Imaging Array
- Target
- Beamsplitter
- LCD
- Acoustic Lens
Acoustocam Ultrasonic Camera

Real Time C-Scan
Acoustocam Ultrasonic Camera

Photo Courtesy of

![imperium](image-url)
The demo consisted of an NDE inspection on composite structure in the Boeing Factory with the NDE equipment monitored and controlled remotely.
Demo Output:
Real Time NDE data stream, Web Cam output, All available to Remote NDE expert and WebEx invitees
Gridlines/Sizing

C-Scan Settings
- GATE START: 0.376"
- GATE WIDTH: 1.147"
- FREQUENCY: 3.5 MHz
- PULSES PER BURST: 2
Remote Expert NDE

What we learned:

- Remote NDE—where a remote NDE expert monitors and controls an inspection—is a viable strategy.
- The Acoustocam Ultrasound Camera is an NDE instrument that is suited to be an integral “end effector” in this strategy.
- Good wireless connection is vital.
- Situational awareness for the remote expert is important.
- More work needs to be done in the “tactics” of exactly how to optimally carry out remote NDE.
Motivation – Why *Advanced*?

- A reliable way of registering 2D NDE scans with the 3D airplane coordinate system is needed.
Advanced Remote Expert NDE

Objective:

• Develop a process to allow remote NDE experts to operate scanning and registration hardware, with minimal assistance from on-site technicians, and then analyze scan results registered in a CAD environment

Approach:

• Integrate existing scanning and measurement hardware and 3D visualization software, along with distributed remote connection techniques to provide an acquisition and analysis system for remote inspection
Benefits:

• This system allows a remote NDE expert to inspect an airplane (or other target object) to determine precise locations in airplane coordinates and identify parts of interest within the scan region by direct comparison of the 2D scan to the associated 3D CAD data.

• Improvements in overall measurement accuracy and documentation, reduction in errors, delays, and potential rework
Advanced Remote Expert NDE

Primary System Components

Local Positioning System (LPS)

Mobile Automated Scanner (MAUS)

Integration Visualization Tool (IVT)
Advanced Remote Expert NDE

Local Positioning System (LPS):

LPS is a Boeing developed coordinate measurement device (with a motorized pan-tilt head, laser range meter, and video camera), with custom software to convert measured positions into the coordinate system of the target object. The system can be controlled remotely over the Internet. The device can also be instructed to move the laser pointer to user specified coordinates on the target.
Advanced Remote Expert NDE

Mobile Automated Scanner (MAUS):

Along with other modalities (like eddy current and ultrasonic resonance) the MAUS can generate ultrasonic amplitude and time-of-flight scans, and can be run remotely using a Remote Desktop display application.
Advanced Remote Expert NDE
Integration Visualization Tool (IVT):

IVT is a Boeing developed 3D visualization system used in all of the BCA commercial airplane programs and also on some BDS programs. It is used for display of large amounts of CAD data for design reviews and analysis tasks. (ivt.web.boeing.com)
Advanced Remote Expert NDE

System Configuration

Target Object

NDI Scanner

On-Site Support Person

Local Positioning System

Network Switch

Inspection Site ("Local" Site)

Internet (Wired or wireless)

Remote Workstation

NDI Expert

Operations Command Center ("Remote" Site)
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Process Flow

NDI Scan System (MAUS)

NDI scan images

3D positions & camera image

Position move commands

2D-to-3D Scan Integration App

Position tracking, 3D point, frame, & line geom

3D point selection

Measure System (LPS)

3D Model Visualization (IVT)
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Results (from an airplane fuselage)

Screenshots:

Ultrasonic Time-of-Flight C-Scan (from MAUS) displayed in 2D image viewer and registration application

3D CAD model environment (IVT) showing extents of 2D ultrasonic scan and locations of areas of interest
Advanced Remote Expert NDE

Results (continued)

Photos from inspection test with an operator at a remote location (left) and a helper at the inspection site (right)
Advanced Remote Expert NDE

Video

Inspection Site

Remote Site
Stills from video
Trends in R&D for Nondestructive Evaluation of In-Service Aircraft

Autonomous NDE
The problem we are trying to address

• On-aircraft inspections are often required as part of the maintenance of aircraft
The problem we are trying to address

• In the commercial aircraft world, most of this inspection is done manually, with hand-held probes.
  – Manpower and cycle times can be high
  – Inspection repeatability, reliability and record keeping is generally low
  – Access to difficult and dangerous locations can cause injury and damage
The problem we are trying to address

- Scanning systems are currently used for inspecting some military aircraft
  - Require access to structure, which may be difficult or dangerous
  - Require manpower to align, attach, move, re-attach, and detach
  - Correlation of scan data to aircraft structure can be challenging
‘Autonomous NDI’ (AuNDI)

Non-Destructive Inspection (NDI) that reduces or eliminates the requirements for human interaction with the structure under inspection or the inspection system itself.

• Utilizes mobile robotic systems
• Applied to aircraft exterior & interior structures
• May have factory, depot, or field use
General system requirements for AuNDI

• Low cost
• Easy to use
• Safe to use
• Does not damage the aircraft
• Require minimal access to structure
• Require minimal human interaction
• Tailored to environment (factory, depot, field, etc.)
• Fast and robust data collection
• Registers NDI data to aircraft
• Autonomous guidance/feedback control capability
Boeing ROVER Automated NDE system

- Local Positioning System (LPS)
- Remotely Operated Vacuum Enabled Robot (ROVER)
- Motion Capture (MoCap)
- NDE Instrument
- Integration Visualization Tool (IVT)

ROVER Feedback Control and NDE Data Registration
LPS is a Boeing developed coordinate measurement device (with a motorized pan-tilt head, laser range meter, and video camera), with custom software to convert measured positions into the coordinate system of the target object. The system can be controlled remotely over the Internet. The device can also be instructed to move the laser pointer to user specified coordinates on the target.
Boeing Local Positioning System (LPS)

LPS Head Components

LPS Controller GUI

System

LPS Head

measured data in context with 3D CAD geometry
Boeing Integration Visualization Tool (IVT):

IVT is a Boeing developed 3D visualization system used in all of the BCA commercial airplane programs and also on some BDS programs. It is used for display of large amounts of CAD data for design reviews and analysis tasks.
Autonomous NDI System
inspecting an upper wing skin

Local positioning system (LPS)

LPS enables scan planning, navigation guidance of autonomous crawler, and data/defect mapping over structural model
This system uses off-the-shelf motion capture hardware initially developed for the movie industry, along with patented (US Patent No. 7,643,893) closed-loop feedback control technology developed by Boeing that leverages motion capture hardware for vehicle tracking and control. This system consists of multiple stationary cameras with integrated illuminators on portable stands or fixed position mounts placed around the target object. This system tracks unique patterns of retro-reflective markers placed on the crawler to determine its position and orientation.
Autonomous NDE – Motion Capture System

Key components:
- **Cable Management System**
- **Safety tether, power and control cables**
- **Mobility platform with Mecanum wheels**
- **Crawler with optical targets on surface (retro-reflective markers)**
- **Array controller**
- **NDE controller**
- **MoCap Camera System**

Description:
- The system involves a mobility platform with Mecanum wheels, a crawler with optical targets on the surface, and a cable management system.
- The safety tether, power, and control cables are managed through the cable management system.
- The mobility platform allows for the motion of the system, while the crawler ensures accurate movement along the surface.
- The MoCap Camera System captures the motion data for analysis.

The images depict the corresponding parts of the system, providing a visual representation of the components and their arrangement.
ROVER – with probe & lit targets
Holonomic Motion with Mecanum Wheels

A holonomic motion vehicle can translate in any direction while simultaneously rotating.

A holonomic vehicle with Mecanum wheels has two type “A” and two type “B” wheels, and four independently controlled motors (one per wheel).
ROVER System

- Safety Boom
- ROVER On-Board Vision System
- LPS Camera/Control Interface
- NDE System Plug-In
- Robot Controller Drive System
- ROVER Crawler

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ROVER Demonstration

ROVER crawling on fuselage
Thank you.