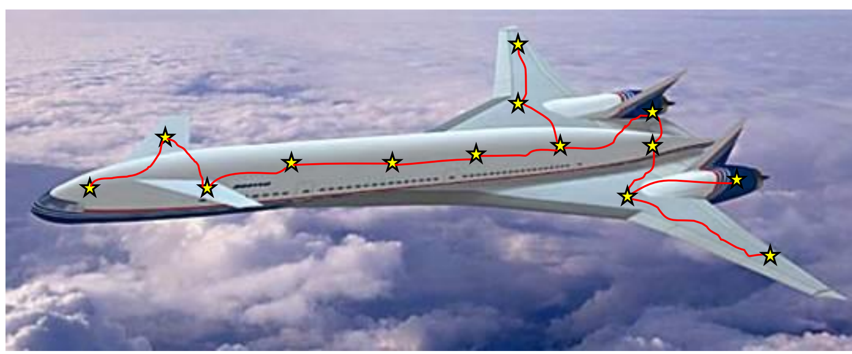
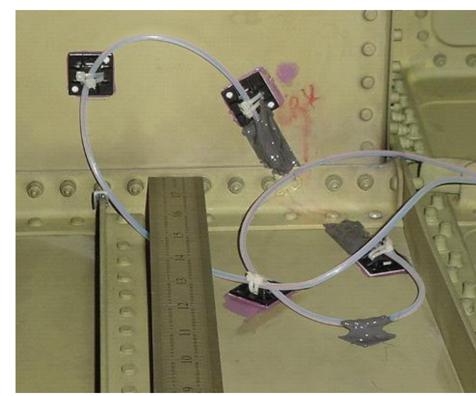
Structural Health Monitoring for Aircraft: Viable Inspection Tool or Passing Fancy?





Dennis Roach
Sandia National Labs
FAA Airworthiness Assurance Center

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Creativity Killers:

“What use could the company make of an electric toy?”
- Western Union, turned down rights to the telephone in 1878

“Who the hell wants to hear actors talk?"
- Harry M. Warner, Warner Bros Pictures, 1927

On usable RAM limit: "640K ought to be enough for anybody."
- Bill Gates, 1981

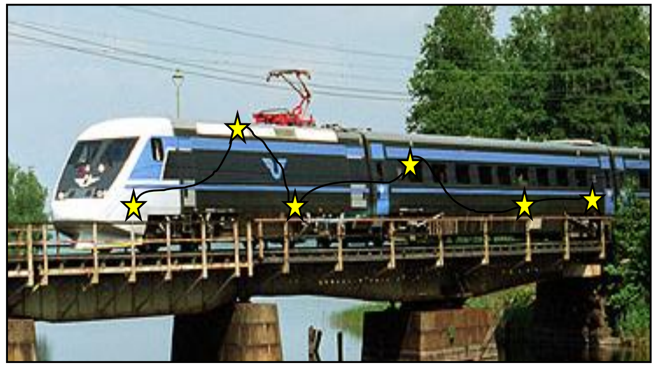
Innovation:

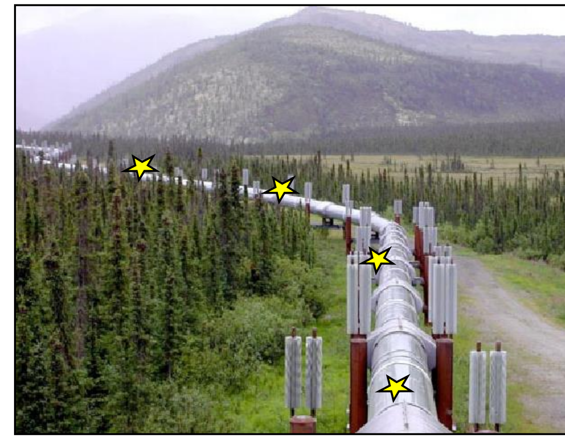
“If you always do what you always did, you will always get what you always got.”
- Albert Einstein

“Two roads diverged in a wood, and I took the one less traveled by and that has made all the difference.”
- Robert Frost

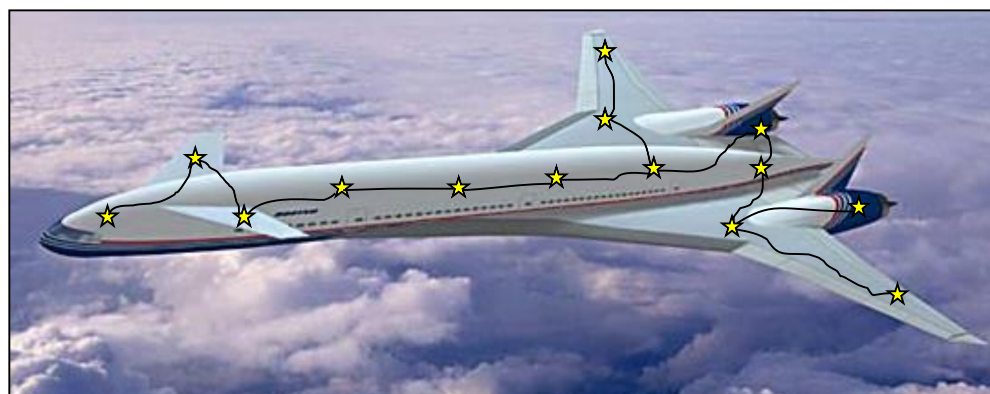
Distributed Sensor Networks for Structural Health Monitoring

Smart Structures: include in-situ distributed sensors for real- time health monitoring; ensure integrity with minimal need for human intervention

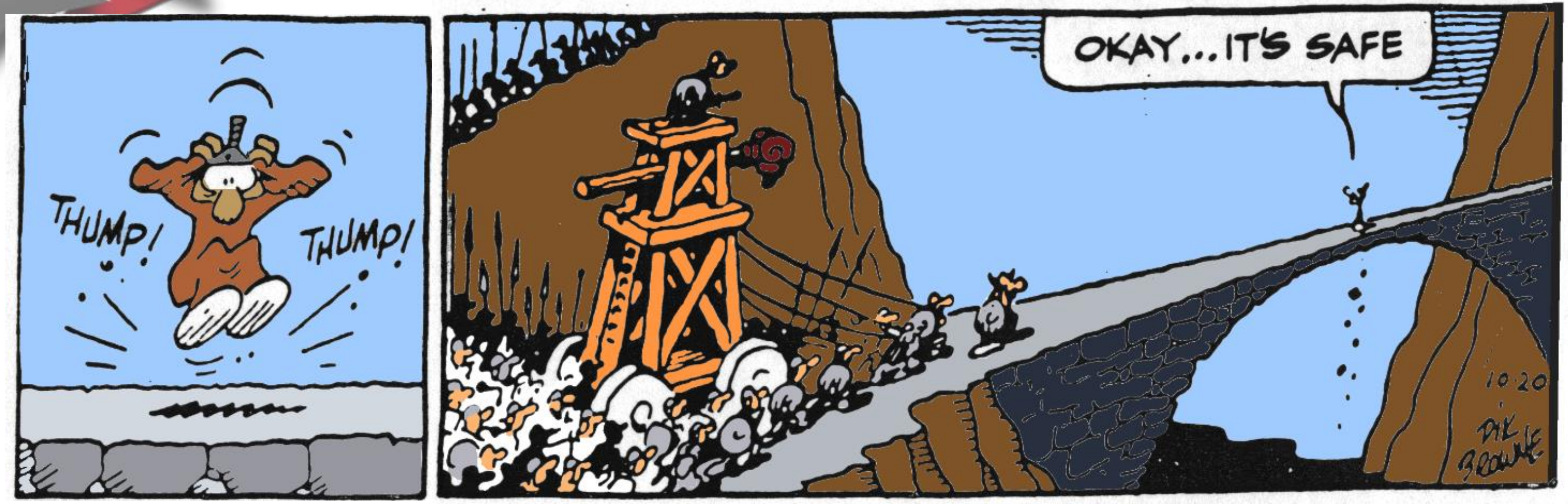




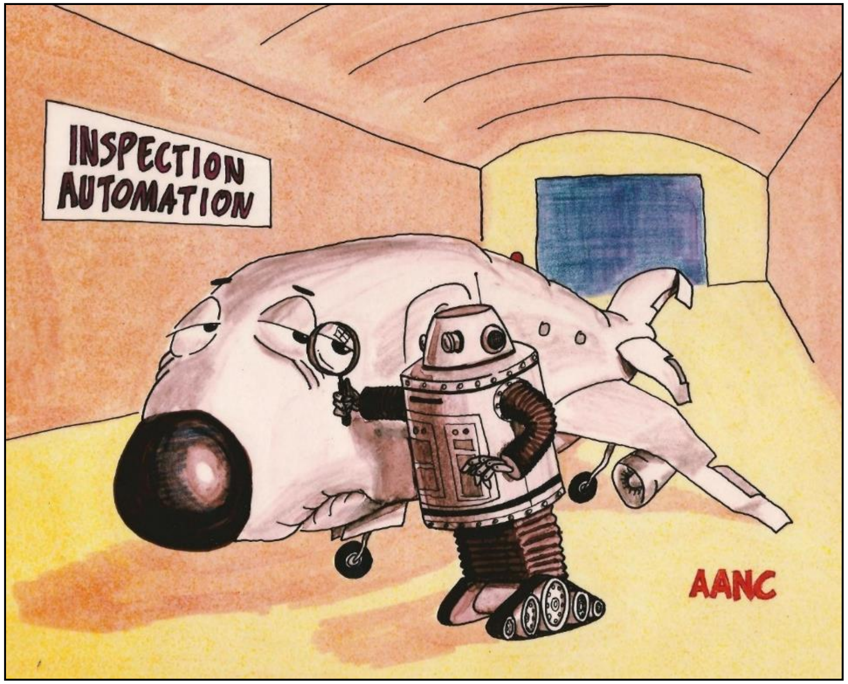
- **Remotely monitored sensors allow for condition-based maintenance**
- **Automatically process data, assess structural condition, & signal need for maintenance actions**



Structural Health Monitoring Dates Back Many Years



Definition is somewhat agreed upon. Usage and deployment covers a wide range of thoughts and options.



NDI vs. SHM – Definition

Nondestructive Inspection (NDI) – examination of a material to determine geometry, damage, or composition by using technology that does not affect its future usefulness

- High degree of human interaction
- Local, focused inspections
- Requires access to area of interest (applied at select intervals)

Structural Health Monitoring (SHM) – "Smart Structures;" use of NDI principles coupled with in-situ sensing to allow for rapid, remote, and real-time condition assessments (flaw detection); goal is to reduce operational costs and increase lifetime of structures

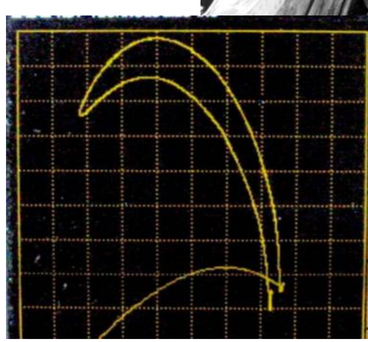
- Greater vigilance in key areas – address DTA needs
- Overcome accessibility limitations, complex geometries, depth of hidden damage
- Eliminate costly & potentially damaging disassembly
- Minimize human factors with automated data analysis

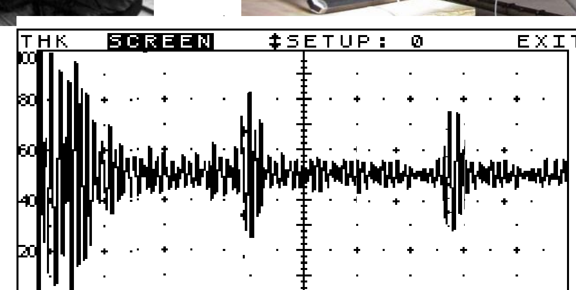
The Trouble with Math or…..
How do we calculate Damage Tolerance ??

Difficulty in loads assignment, stress and fatigue calculations produces demands on NDI - "You want me to find a flaw where, and how small??"

Difficult Conditions

Lots of Rapid Data Interpretation





Benefits of SHM

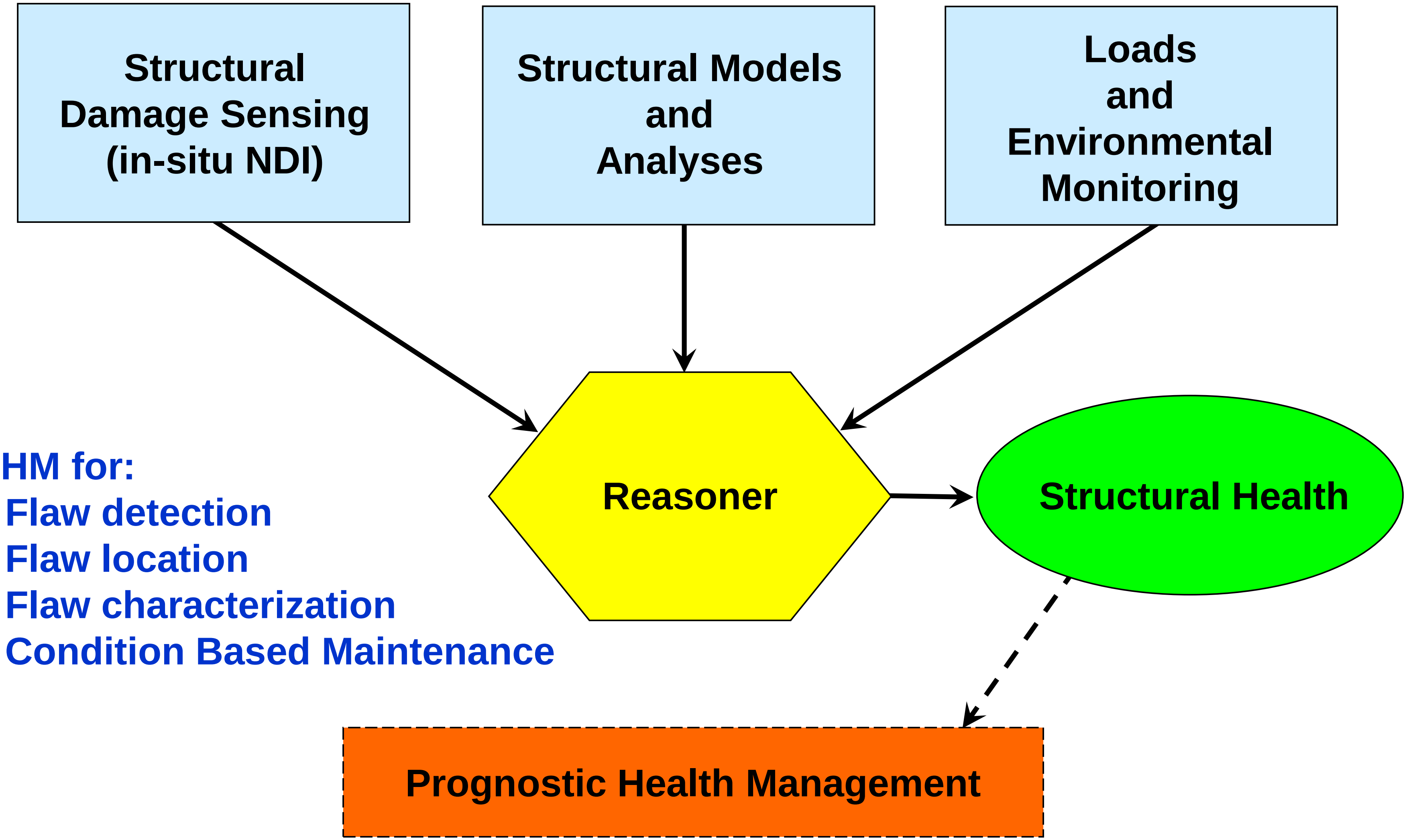
Near-Term

- Elimination of costly & potentially damaging structural disassembly
- Reduced operating and maintenance costs
- Detection of blunt impact events occurring during normal airplane operations
- Reduction of inspection time
- Overcome accessibility & depth of flaw impediments
- Early flaw detection to enhance safety and allow for less drastic and less costly repairs
- Minimized human factors concerns due to automated, uniform deployment of SHM sensors (improved sensitivity)
- Increased vigilance with respect to flaw onset

Long Term

- Optimized structural efficiency
- New design philosophies (SHM designed into the structure)
- Weight savings
- Substitution of condition-based maintenance for current time-based maintenance practices

Structural Health Monitoring



SHM for:

- Flaw detection
- Flaw location
- Flaw characterization
- Condition Based Maintenance

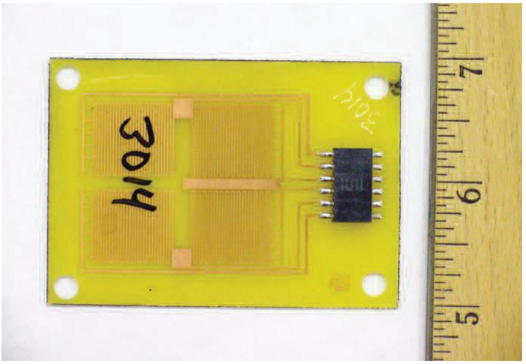
SHM Impediments & Challenges

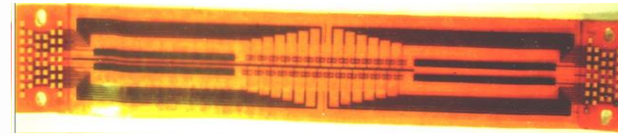
- Cost of sensors and sensor systems and airworthiness requirements
- Ease of use and coverage area - small-scale damage must be detected in large-scale structures
- Time for after-market installations - inconvenient MTC visits
- Need for rapid customization of sensors
- Need for substantial business case (cost-benefit analysis) – operators must realize benefits of multi-use
- Who own's technology? (centralized OEM approach may be best/safest)
- Validation activities – reliability of SHM systems must be demonstrated
- Validation activities – field trials on operating aircraft is necessary but time consuming
- Certification – need to streamline specific applications; technical, educational and procedural initiative (OEMs, operators, regulators)
- Standardization needed for validation and certification activities
- Implementation requires changes in maintenance programs

Is Structural Health Monitoring a Viable Alternative Today?

- Evolution of miniaturized sensors & supporting technology
- Design of turnkey systems with reasonable costs
- Ability to monitor new & unexpected phenomena (new inspection needs; DTA and rapid flaw growth)
- Promise for technical & economic gains more clearly defined
- OEM willingness to explore SHM merits
- Long-term prognosis -
  - ➢ Complete health assessment with network of SHM "nerves"
  - ➢ Automated data transmission (real-time monitoring; alarms)
  - ➢ Embedded sensors (MEMS)
  - ➢ Improved diagnostics using neural networks (historical data)
  - ➢ Direct ties to maintenance planning and actions
  - ➢ Reduction in life-cycle costs

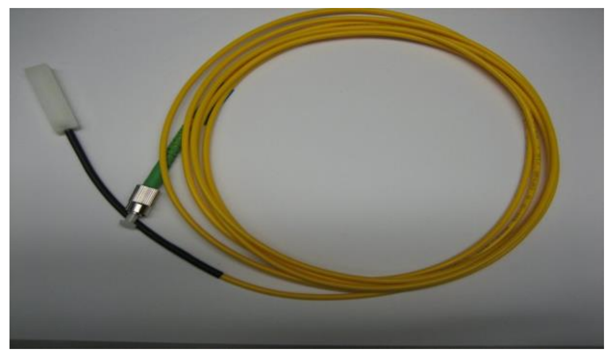
Sampling of SHM Sensors



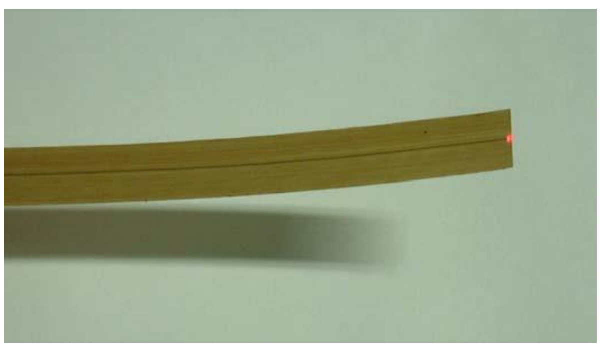


Cumulative Environmental Corrosion Sensor

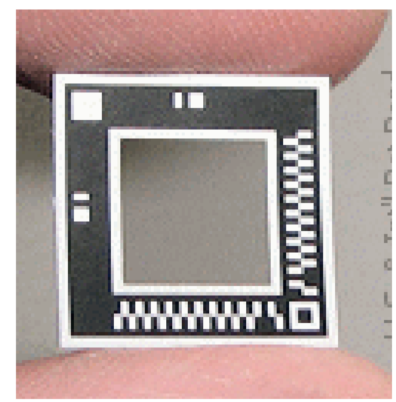
Flexible Eddy Current Array Probe



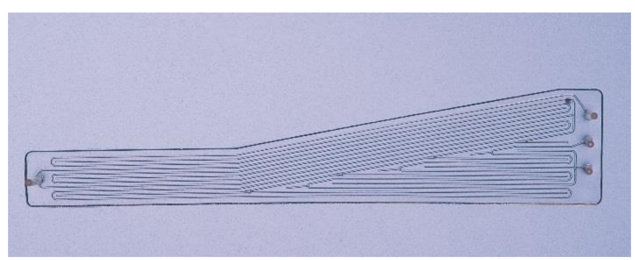
Vibro Fibre SHM Sensor



SMARTape Membrane Deformation Sensor



Direct Measurements Strain Sensor



Comparative Vacuum Monitoring Sensor

Synopsis of SHM Validation/Utilization Programs Supporting Safe Adoption of SHM Systems

Timeline

2005

FAA — General SHM Validation

- Assess performance for fuselage applications
- Lab & field testing
- CVM adoption into Boeing NDT Standard Practices Manual

2008

FAA — SHM R&D Roadmap

- Industry survey
- SHM TRL assessment
- Industry perspectives
- Validation methodology
- Considerations for regulatory guidance

2010

FAA — SHM for Commuter Aircraft

- Trial on known damage prone area
- Successful detection on-aircraft
- Transport Canada participation
- Assess repair as-needed

2012

Embraer — Certification for Families of SHM

- CVM & PZT usage over range of A/C applications
- Quantify performance
- Use approval via SBs
- ANAC & FAA interface

2014

FAA — SHM Certification & Adoption by Airlines

- Specific CVM application
- Joint with FAA, Sandia Labs, Delta Air Lines & Boeing
- Formal validation & flight tests
- CVM added to NDT Manual
- SB released – first routine use of SHM

2016

FAA — SHM for Rotorcraft

- Validation of local & global SHM approach
- Process for routine use
- Integration into rotor maint.
- Mock certification with FAA
- Integration into HUMS

Boeing — SHM for Aft Pressure Bulkhead

Structural Health Monitoring – Integration into Routine Maintenance

Program Participants

Sandia National Laboratories: Dennis Roach, Tom Rice, Stephen Neidigk

Federal Aviation Administration: Paul Swindell, Dave Galella, Ian Won, Mark Freisthler

Delta TechOps: David Piotrowski, Alex Melton, John Bohler, Joe Reeves, Chris Coleman, John Hays

Bombardier: Jérôme Pinsonnault, Colin Vollrath, Yves Theriault

Boeing: John Linn, Jeff Kollgaard

Structural Monitoring Systems: Toby Chandler, Mike Reveley, Andy Chilcott

Anodyne Electronics Manufacturing Corp.: Trevor Lynch-Staunton, Henry Kroker, Brian Shiagec, Dave Veitch

Air Canada: Bernie Adamache, Joe Zee

Embraer: Ricardo Rulli, Fernando Dotta, Paulo Anchieta, Luis Santos

Transport Canada: John Mitchell, Hin Tsang, Maurizio Molinari, Marc Lord

Sikorsky: Mark Davis, Andrew Brookhart, Preston Bates, Ray Beale

Acellent: Amrita Kumar, Fu-Kuo Chang, Howard Chung, Franklin Li

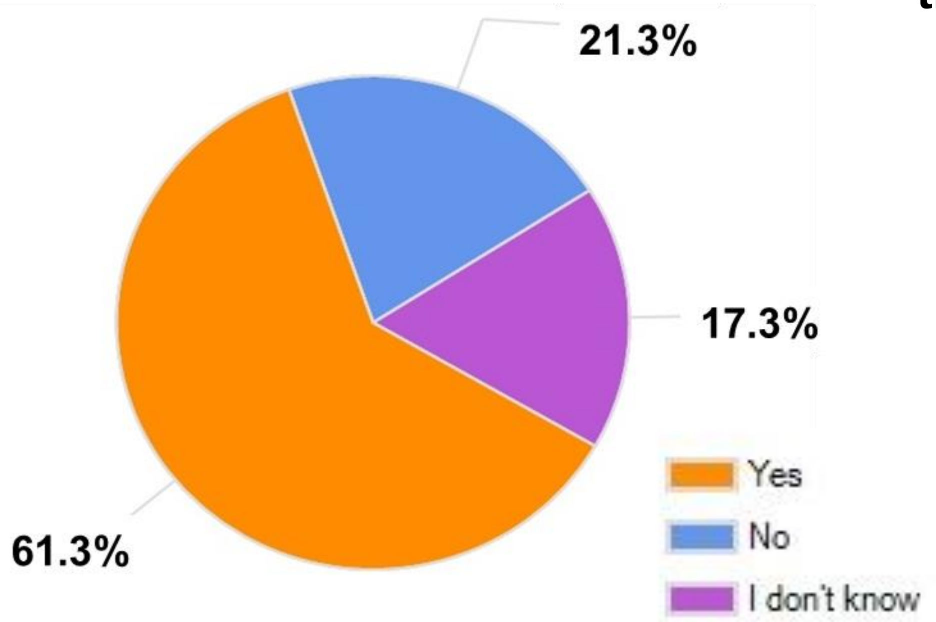
SHM Survey of Aviation Industry

Owners/Operators	OEMs	Regulators	Maintainers
All Nippon Airways American Airlines Austrian Air Force China Airlines Continental Airlines Delta Air Lines Federal Express Finnair Hawaiian Airlines Japan Airlines Jazz Airlines Jet Blue Airways Kalitta Air LLC NASA Qantas Airways Singapore Airlines Swiss Air United Airlines US Airways USAF US Army USCG US Navy	Airbus Astronics-Adv. Electronic Systems Avensys Inc. BAE systems Bell Helicopter Textron Boeing Bombardier Aerospace Cessna Aircraft Company Dassault Aviation EADS Military Air Systems Embraer Goodrich Honeywell Lockheed Martin Aeronautics Messier-Dowty Mistras Group, Inc Polskie Zaklady Lotnicze Sp. PZL Swidnik Rolls-Royce Corp Systems & Electronics, Inc. TecScan	Air Transport Association CAA - NL CAA - Bra EASA FAA NAVAIR NAWCAD Transport Canada (TCCA) USAF US Army USCG US Navy	Aerotechnics Inc Air New Zealand China Airlines Christchurch Engine Centre Fokker Aircraft Services B.V. Fuji Heavy Industries, Ltd. Jazz Air LTD Lufthansa Technik AG NASA Olympic Airways Services S.A. SAA Technologies SR Technics Switzerland LTD Texas Aero Engine Services Timco / GSO United Airlines USAF US Army USCG US Navy

Over 450 responses from OEMs, regulators, operators, and research organizations.

SHM Survey Results – Viability & Airline/OEM Usage

Viability of Using SHM as an Alternative Solution to NDT



Does the sensor have a fail-safe feature which will prevent the acquisition of faulty data from a damaged or failed sensor?

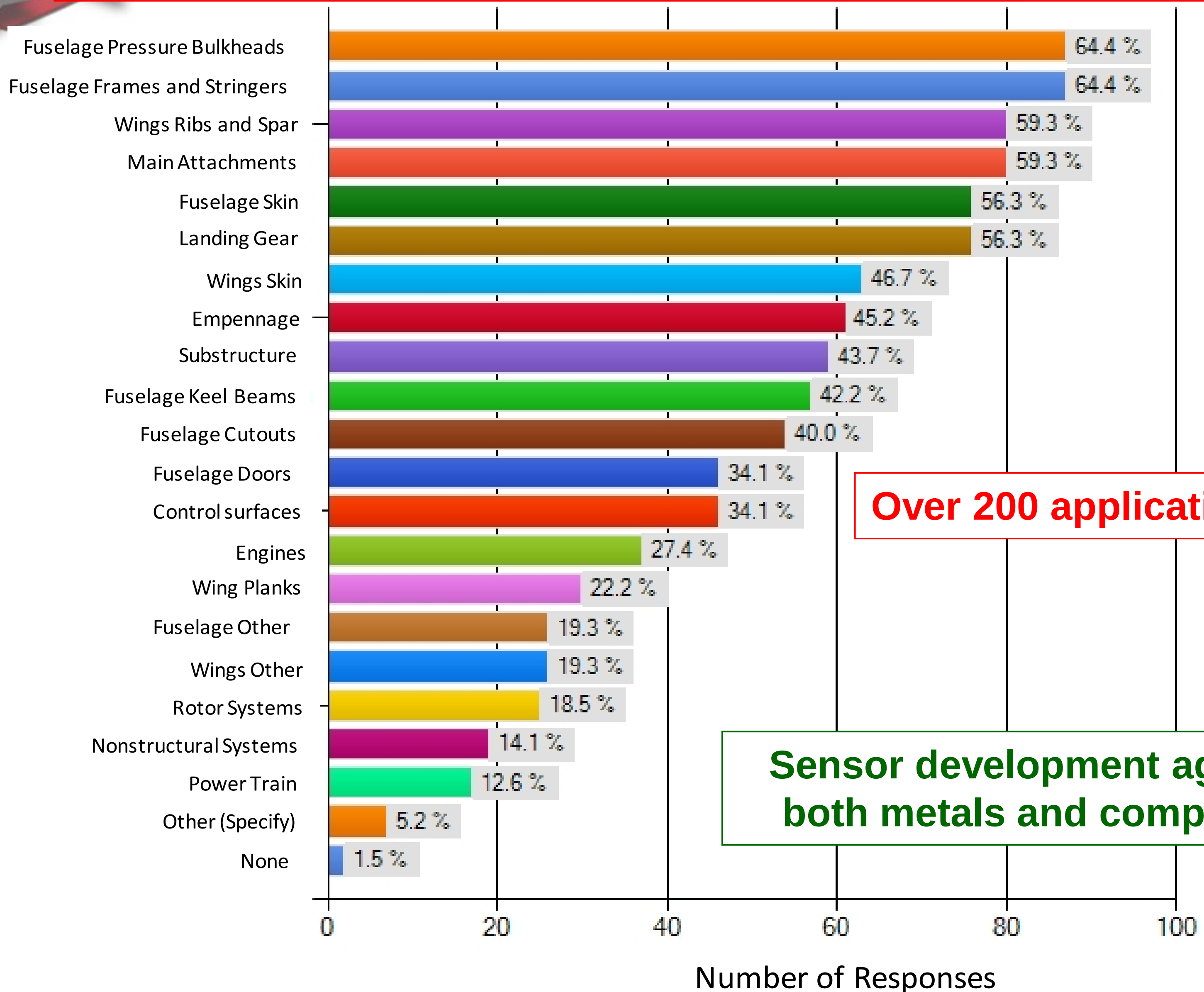
52% Yes
48% No

Does the system contain a built-in self-diagnostic capability to automatically interpret the data?

60% Yes
40% No

- **55% of aircraft operators, maintainers, and military personnel say that 5 years is a reasonable payback period for recouping the cost associated with using an SHM system**
- **31% say 2 years is reasonable**

Areas Respondents Feel SHM Solutions are Viable



Over 200 applications listed

Sensor development agrees – both metals and composites

Aerospace Industry Steering Committee on Structural Health Monitoring (AISC SHM)

First meeting of AISC-SHM
Stanford University
Palo Alto, CA
October 2006

Recognized need for guidance and standardization

20th meeting of AISC-SHM
OGMA MRO
Lisbon, Portugal
April 2016

ARP – Guidelines for SHM Implementation

- **The mission of the AISC-SHM is to provide an approach for standardizing integration and certification requirements for SHM of aerospace structures, which will include system maturation, maintenance, validation and introduction into accepted maintenance practices.**

- **The focus is the <u>development of cross-industry guidebooks</u> describing approaches to safely deploy SHM systems on fixed wing aircraft and rotorcraft and guidelines for the proper validation and certification of SHM solutions.**

- **SAE International Aerospace Recommended Practices document: ARP6461 "Guidelines on the Implementation of Structural Health Monitoring on Fixed Wing Aircraft" (September 2013)**

SAE Aerospace — An SAE International Group

AEROSPACE RECOMMENDED PRACTICE

SAE ARP6461

Issued: Proposed Draft 2012-11-28

Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft

DRAFT

RATIONALE

The development of Structural Health Monitoring (SHM) technologies to achieve Vehicle Health Management objectives in aerospace applications is an activity that spans multiple engineering disciplines. It is also recognized that many stakeholders: Regulatory Agencies, Airlines, Original Equipment Manufacturers (OEM), Academia and Equipment Suppliers are crucial to the process of certifying viable SHM solutions. Thus a common language (definitions), framework of solution types, and recommended practices for reaching those solutions, are needed to promote fruitful and efficient technology development.

TABLE OF CONTENTS

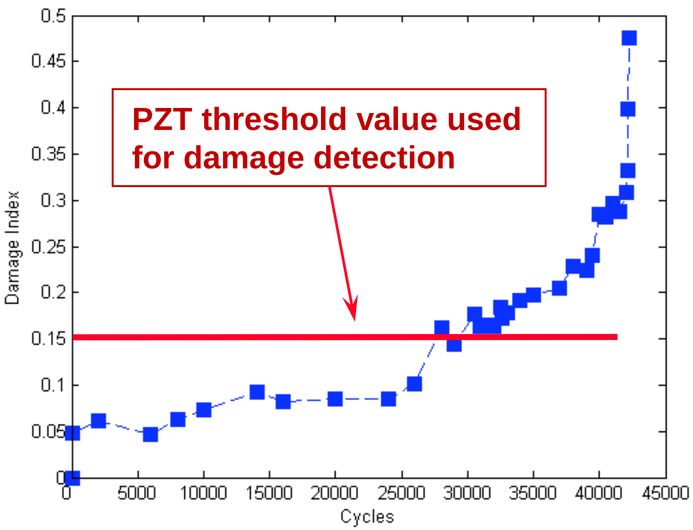
1. SCOPE ... 5
1.1 Purpose ... 5
1.2 Field of Application ... 5
1.3 An Overview of This Document ... 6
1.3.1 General Approach ... 6
1.3.2 Designing and Maintaining Airworthy Structures ... 6
1.3.3 Evolution of Aircraft Products Including Structures and SHM Systems ... 7
1.3.4 Requirements, V&V, and Certification ... 7

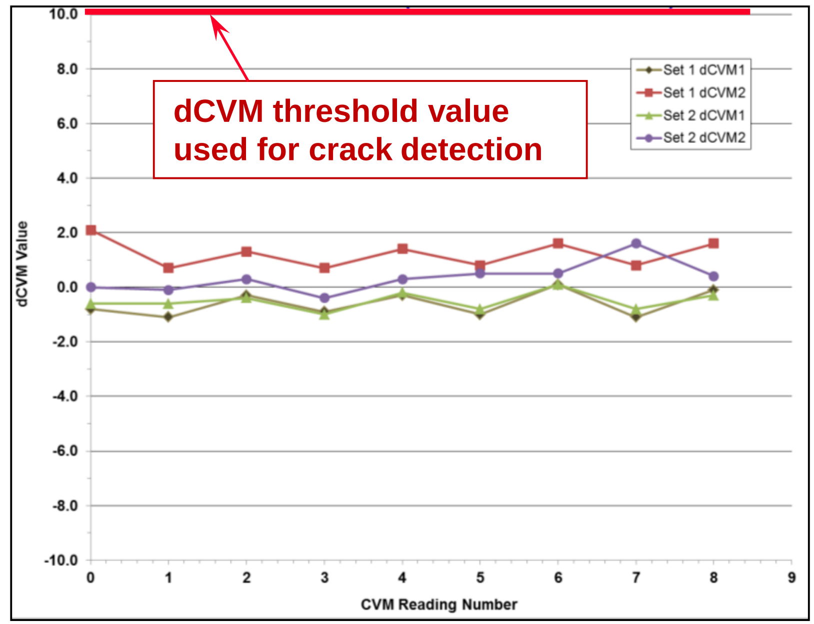
2. REFERENCES ... 9
2.1 Applicable Documents ... 9
2.1.1 SAE Publications ... 9
2.1.2 FAA Publications ... 9
2.1.3 EASA Publications ... 10
2.1.4 TCCA Publications ... 10
2.1.5 RCTA Publications ... 10
2.1.6 A4A Publications ... 11
2.1.7 U.S. Government Publications ... 11
2.1.8 Other Publications ... 11
2.2 Related Publications ... 11
2.3 Definitions ... 11
2.4 Acronyms ... 13

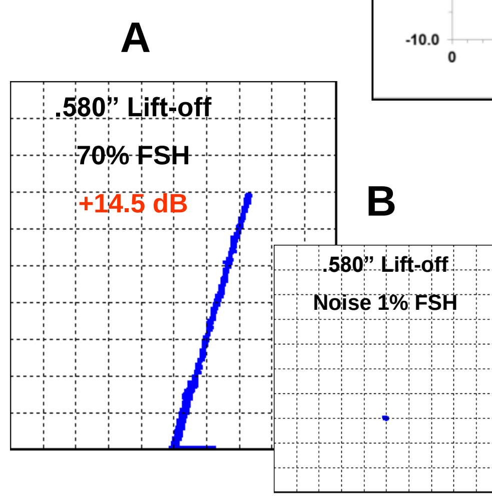
3. INTRODUCTION TO AIRCRAFT STRUCTURES DESIGN AND MAINTENANCE ... 15
3.1 Structures Design Principles ... 15
3.2 Current Structures Maintenance Principles ... 17
3.2.1 A4A MSG-3 Document ... 17
3.2.2 FAA AC 121-22 "Maintenance Review Board Procedures" ... 18
3.2.3 Other Instructions for Continued Airworthiness ... 18
3.3 Summary ... 19

SHM Information – Minimize Intrepretation or Data Analysis

- Automated data analysis is the objective – produce a "Green Light – Red Light" approach to damage detection
- Final assessment and interpretation by trained NDI personnel



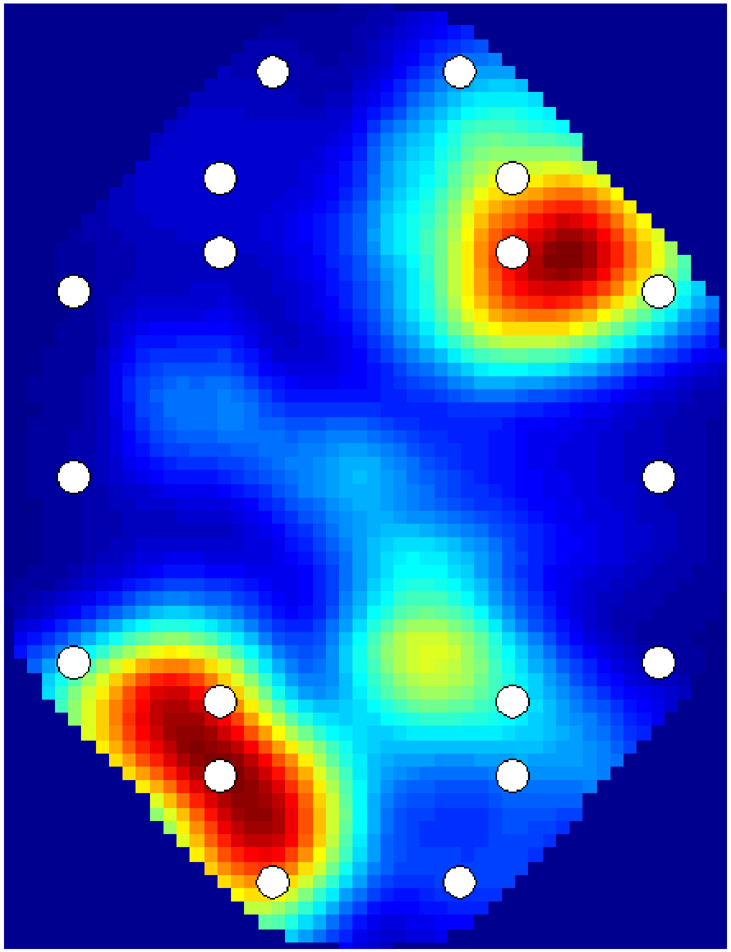




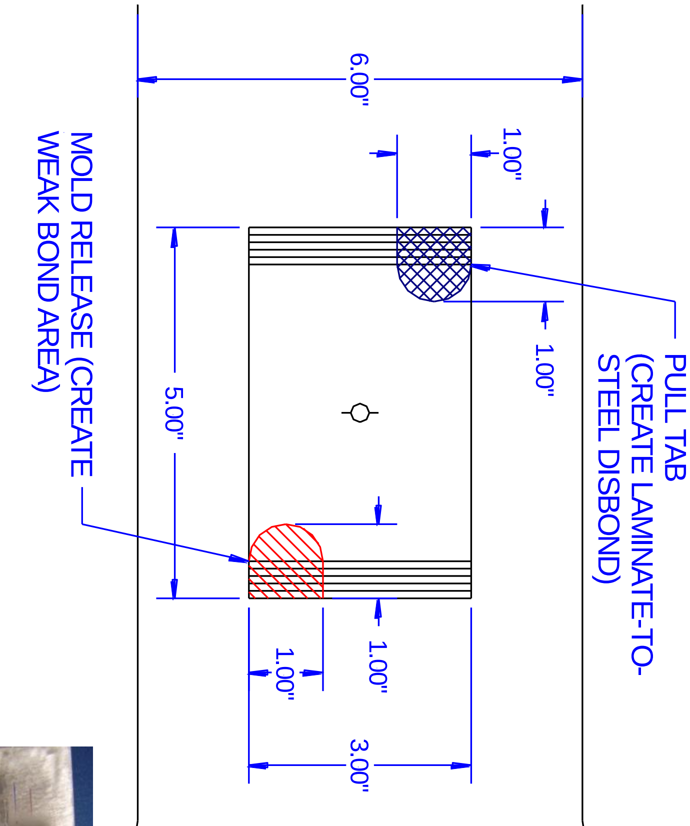
A = Sensor Response to Crack (flaw signal)

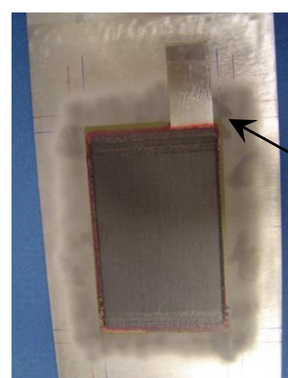
B = Sensor Response at Uncracked Region

Disbond Detection & Growth Monitoring with Piezoelectric Sensors



After mold release flaw growth (50 KHz inspection)



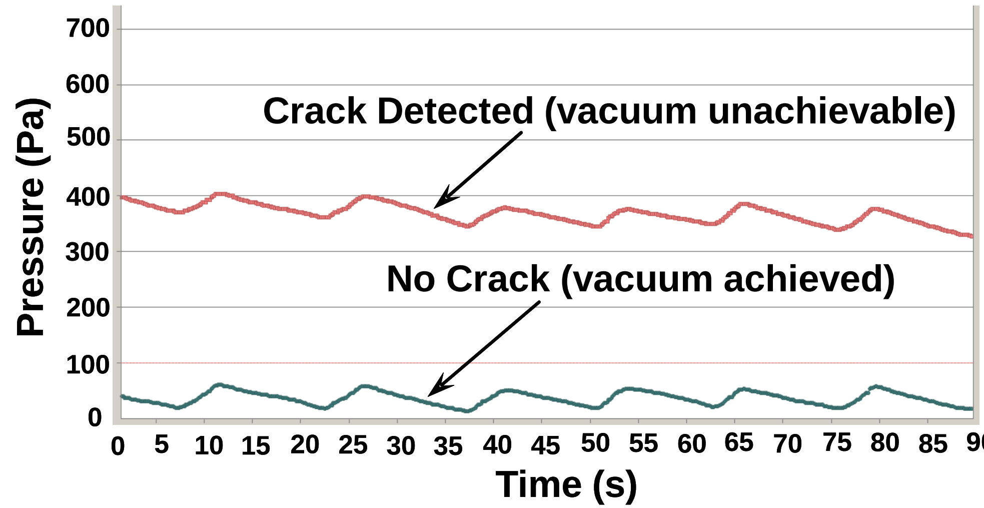


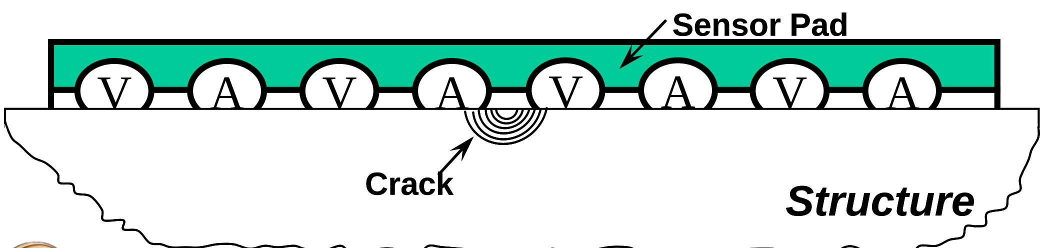
Pull tab flaw

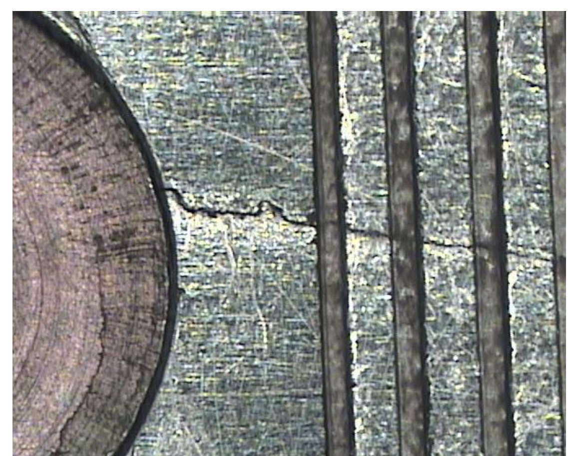
Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries (crack detection < 0.1” for alum. < 0.1” th.)
- Leakage path produces a measurable change in the vacuum level
- Doesn’t require electrical excitation or couplant/contact

CVM Sensor Adjacent to Crack Initiation Site

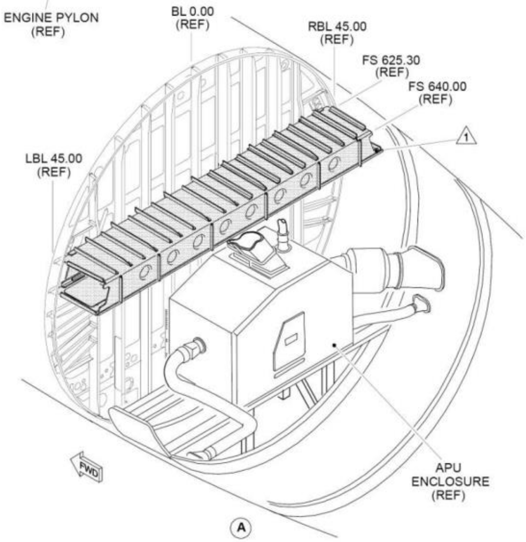




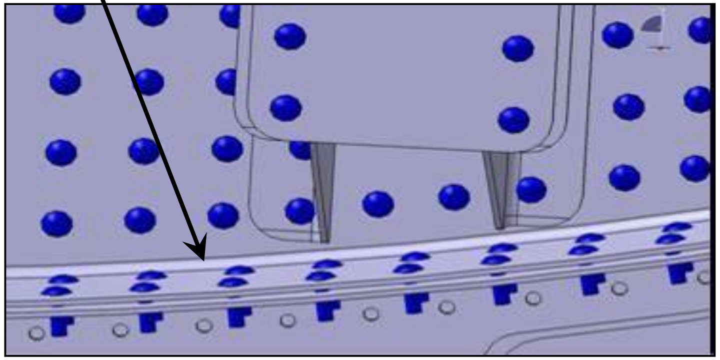


CVM Success on CRJ Aircraft

Pilot program with Bombardier and Air Canada



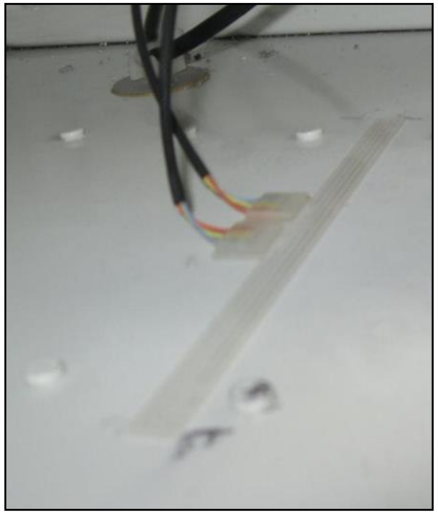
Inspect in the radius

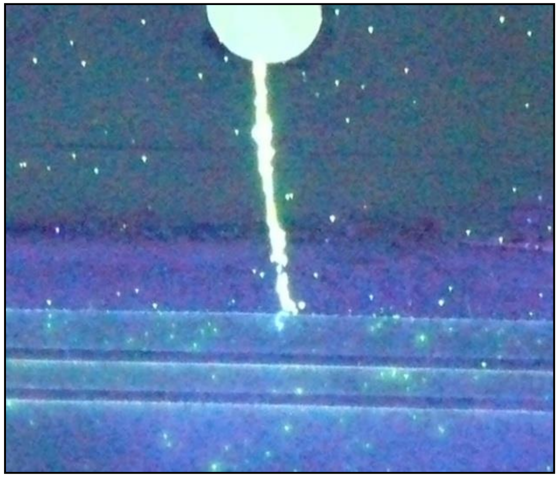


Sensor Issues:

- Design
- Surface preparation
- Access
- Connection
- Quality control

Aft Equipment Bay

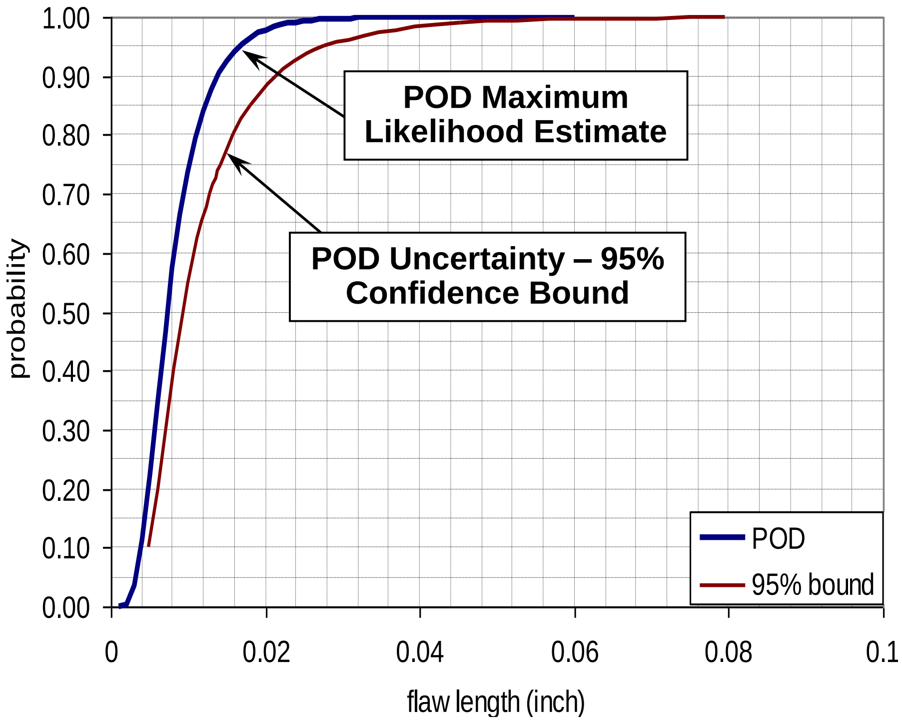




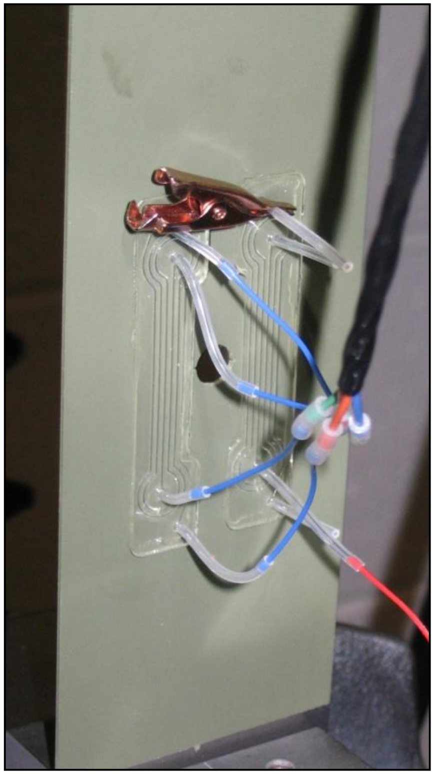
CVM - Quantified Probability of Crack Detection for a Range of Variables

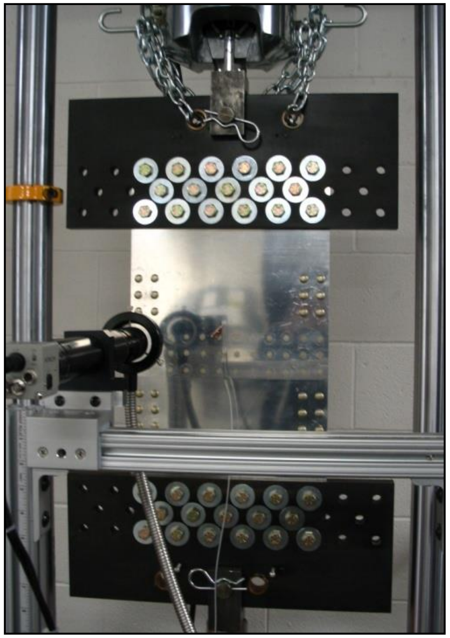
Test Scenarios:

Material	Thickness	Coating
2024-T3	0.040”	bare
2024-T3	0.040”	primer
2024-T3	0.071”	primer
2024-T3	0.100”	bare
2024-T3	0.100”	primer
7075-T6	0.040”	primer
7075-T6	0.071”	primer
7075-T6	0.100”	primer



Cumulative Distribution Function of Detectable Flaw Lengths (0.040” th. primer panels)

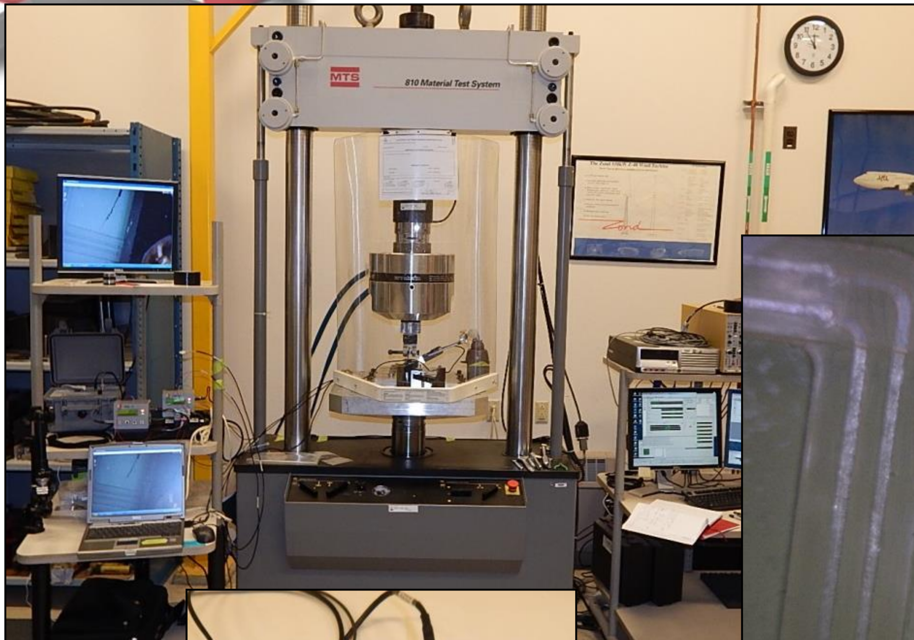




CVM Sensor Network Applied to 737 Wing Box Fittings

Alternate Means of Compliance with Current Visual Inspection Practice

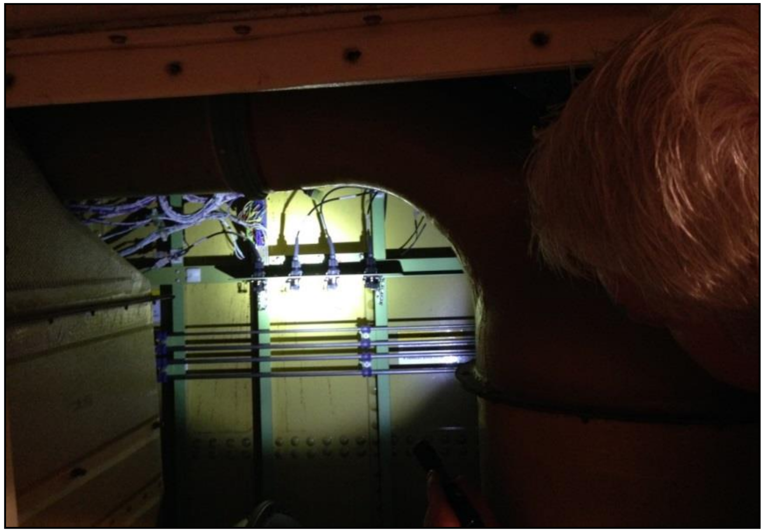
737NG Center Wing Box – CVM Performance Tests



737NG Center Wing Box – Accumulating Successful Flight History

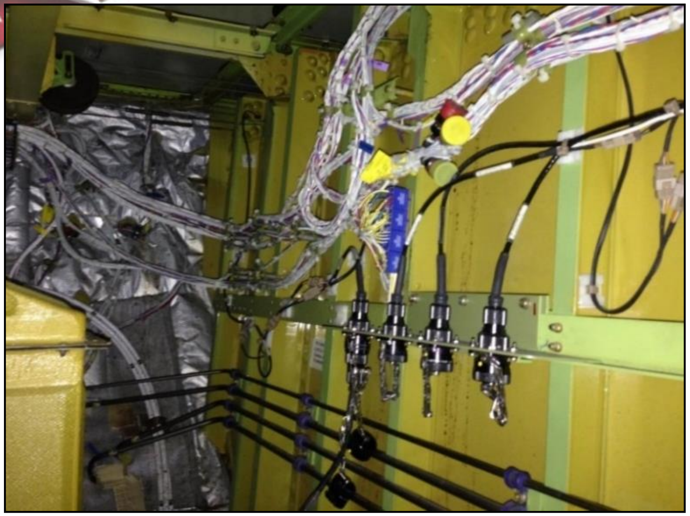
Aircraft Parked at Gate After Final Flight of the Day

Access to SLS Connectors Through Forward Baggage Compartment



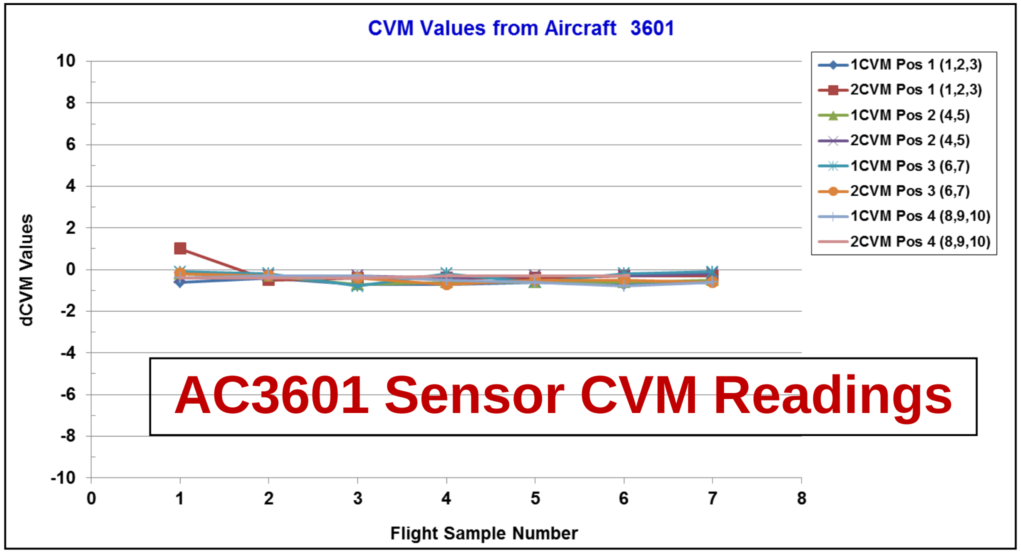
Removal of Baggage Liner to Access 4 SLS Connectors Mounted to Bulkhead

737NG Center Wing Box – CVM Sensor Monitoring



Connecting SLS Leads and Running PM-200 to Monitoring Device to Check Sensor Network

Logging Inspection Completion at Aircraft Gate



FAA William J. Hughes Technical Center

Sandia National Laboratories

737 NDT Manual - New SHM Chapter Published (Nov 2015)

Building Block to Approval for Routine Use of SHM

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- ☑ PART 04 - ULTRASONIC
- ☑ PART 05 - COMPARATIVE VACUUM MONITORING
- ☑ PART 06 - EDDY CURRENT
- ☑ PART 09 - THERMOGRAPHY
- ☑ PART 10 - VISUAL/OPTICAL

Changed to

PART 05 – STRUCTURAL HEALTH MONITORING

737 NDT Manual – CVM Procedure Added

BOEING

737
NON-DESTRUCTIVE TEST MANUAL

PART 5 - COMPARATIVE VACUUM MONITORING

WING CENTER SECTION - SHEAR FITTINGS AT THE FRONT SPAR

1. Purpose
   - A. Use this comparative vacuum monitoring (CVM) procedure to help find cracks in the 111A2401-1 and -2 shear fittings at the front spar of the wing center section. See Figure 1 for the inspection areas.
   - B. This procedure can find cracks that are 0.75 inch (19.1 mm) long or longer.
   - C. The shear fittings are 7050-T7451 aluminum alloy.
   - D. Service Bulletin Reference:
     - (1) 737-57-1309
2. Equipment
   - A. General
     - (1) Comparative vacuum monitoring (CVM) is a structural health monitoring (SHM) system. The CVM system measures the different pressures between sensor galleries that have a vacuum or are at atmospheric pressure to find cracks in parts. See Figure 2 for some examples of CVM equipment.
     - (2) Use the equipment specified in this inspection procedure to do this procedure.
   - B. Instrument
     - (1) PM200; Structural Monitoring Systems (SMS)
   - C. Functional Test Socket
     - (1) PM200-9 or SP1131; Structural Monitoring Systems (SMS)
   - D. Comparative Vacuum Monitoring kit
     - (1) 737NG-FSSF-1KCVM CVM Installation Kit; Structural Monitoring Systems (SMS)
   - E. Software
     - (1) PM200 Management Software version 0.0.3276 or newer
   - F. Special Tools
     - (1) Consumables kit. See set up file: Part 5, 57-10-01 List of Necessary Materials
3. Prepare for the Inspection
   - A. See Set Up File Part 5, 57-10-01, for the List of Necessary Materials.
   - B. See Set Up Files Part 5, 57-10-01, CVM installation instructions for the instructions that follow:
     - (1) Prepare the surface of the 111A2401-1 and -2 shear fittings for inspection.
     - (2) Install the CVM sensors onto the shear fittings.
     - (3) Install the CVM leads.
     - (4) Install four sensor lead sockets (SLS) on the (SLS) bracket.
4. Instrument Calibration and Functional Test

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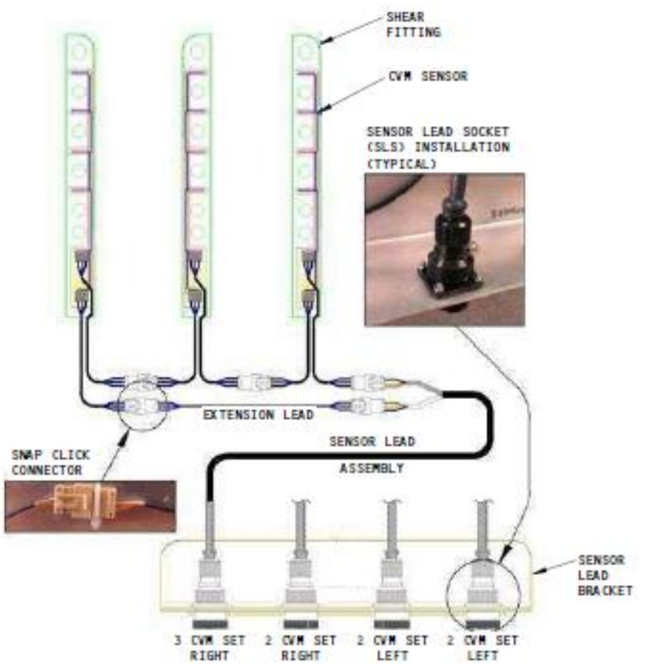
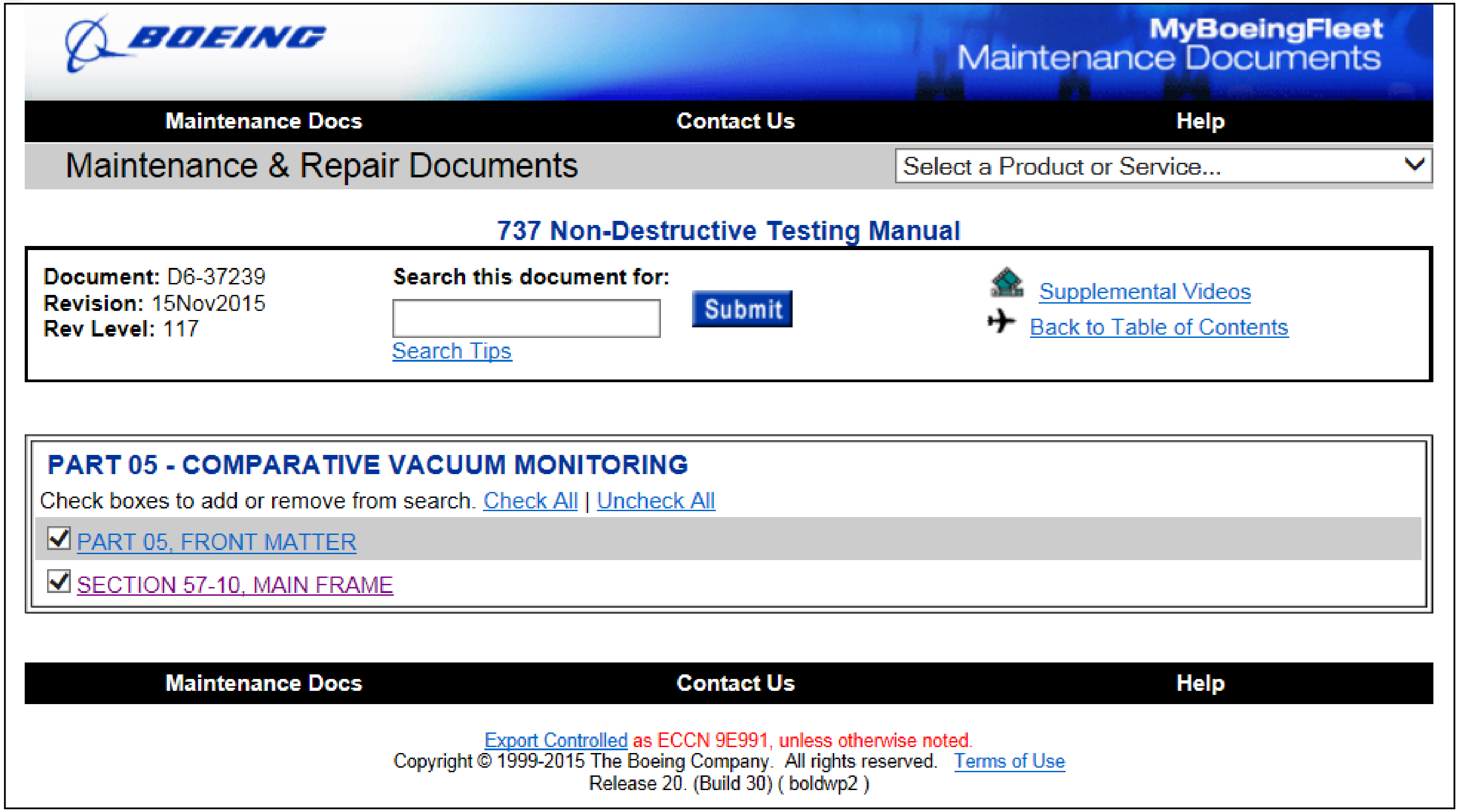
NON-DESTRUCTIVE TEST MANUAL



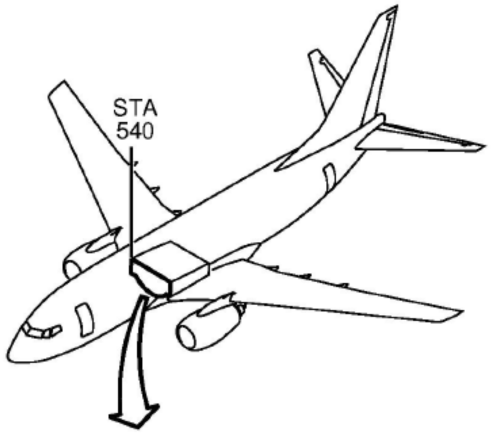
737 NDT Manual – CVM Installation Instructions Added (Jan 2016)



Installation Instructions

Boeing Service Bulletin – Modification to Allow for Routine Use of SHM Solution (June 2016)

BOEING SERVICE BULLETIN 737-57-1309



DO A DETAILED INSPECTION OR COMPARATIVE VACUUM MONITORING (CVM) INSPECTION OF THE CENTER WING BOX FRONT SPAR SHEAR FITTINGS FOR ANY CRACKS. IF ANY CRACK IS FOUND, REMOVE THE DAMAGED SHEAR FITTING, MAKE SURE THERE IS NO CRACKING IN THE UPPER PANEL AND INSTALL A NEW SHEAR FITTING AS GIVEN IN THIS SERVICE BULLETIN.

AT EACH SHEAR FITTING, IF NO CRACKING IS FOUND IT IS OPTIONAL TO ACCOMPLISH THE PREVENTIVE MODIFICATION BY REPLACING THE SHEAR FITTINGS.

BOEING Commercial Airplanes

737
Service Bulletin

Number: **737-57-1309**
Original Issue: January 28, 2011
Revision 1: June 27, 2016
ATA System: 5714

Revision Transmittal Sheet

SUBJECT: WINGS - Center Wing Box - Front Spar Shear Fitting - Inspection, Repair and Preventive Modification

This revision includes all pages of the service bulletin.

COMPLIANCE INFORMATION RELATED TO THIS REVISION

Effects of this Revision on airplanes on which Original Issue was previously done:

None.

REASON FOR REVISION

This revision is sent to add a Comparative Vacuum Monitoring (CVM) inspection as an alternative inspection method for the front spar shear fitting. In addition, illustrations in figures are changed to show correct views, footnotes are added in fastener tables for clarification and footnotes in figures are changed to clarify sealing instructions.

Overview of SHM Readiness

- Overall, there is a strong interest in SHM – multitude of applications covering all aircraft structural, engine, and systems areas
- Industry's main concern with implementing SHM on aircraft is achieving a positive cost-benefit & time to obtain approval for SHM usage
- Research and development efforts should be focused on: global systems, sensor technology, system validation and integration, and regulatory guidance
- Standardization and guidelines are needed in certification, laboratory and field validation, and sensor design with aviation in mind
- SHM will run in parallel with current NDI inspections for a period of time – accumulation of successful flight history will mitigate/eliminate this
- Industry would use SHM to detect cracks, delaminations, disbonds, corrosion and impact among others
- There is a wide variety of SHM sensors currently developed that have shown potential in aircraft applications. SHM maturity has grown exponentially so desired usage and need for certification is expected to rise rapidly.

SHM is the next level of NDT = it's coming soon

Structural Health Monitoring for Aircraft: Viable Inspection Tool or Passing Fancy?