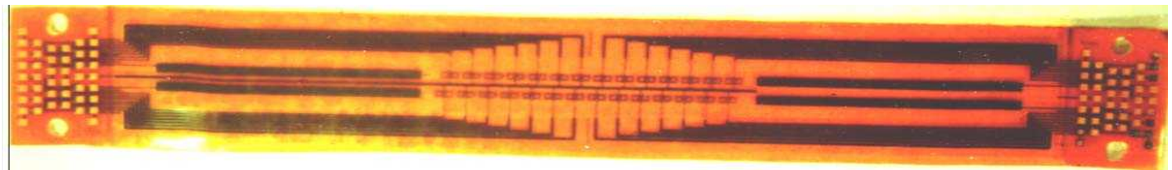
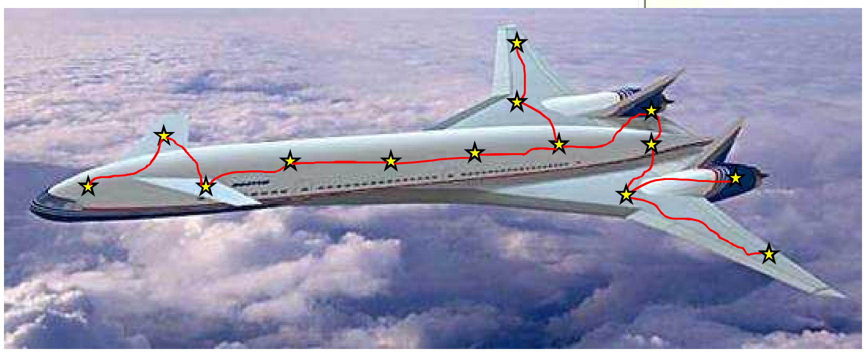
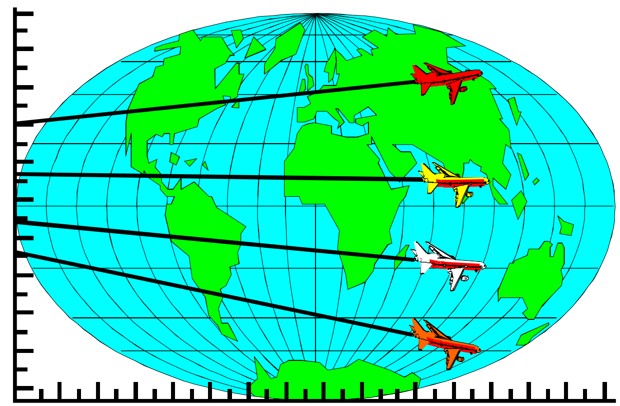
Validation and Verification Processes to Certify SHM Solutions for Commercial Aircraft Applications

SAND2013-7867C







Dennis Roach
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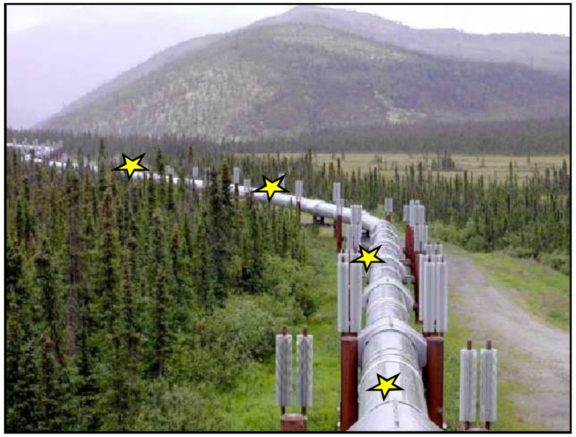
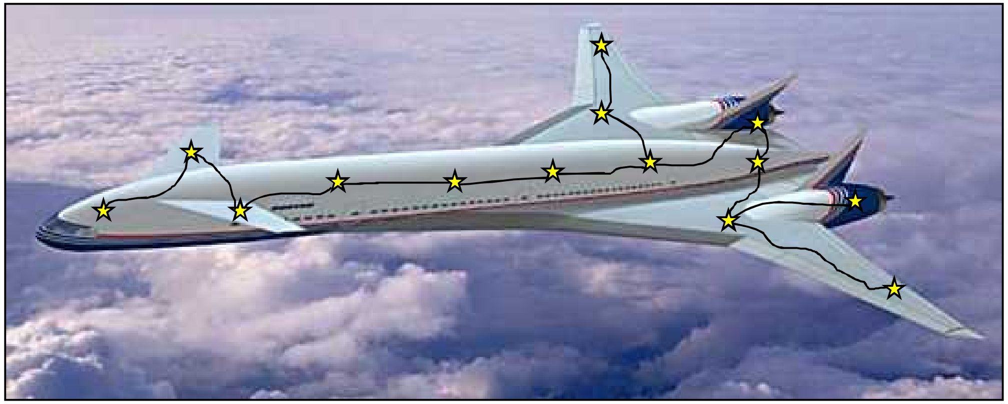
Distributed Sensor Networks for Structural Health Monitoring

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



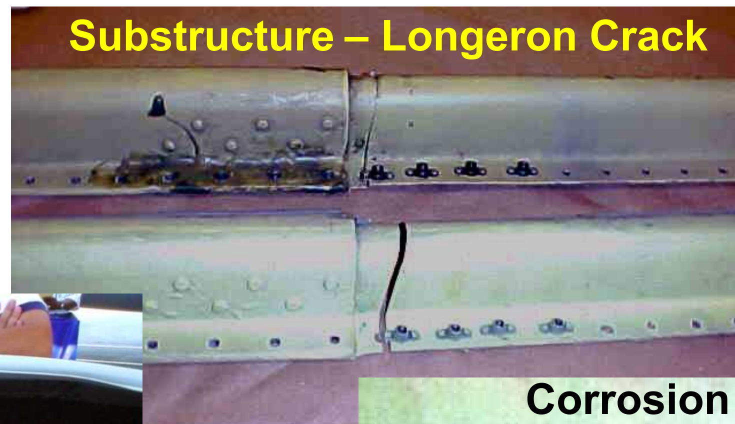
- Remotely monitored sensors allow for condition-based maintenance
- Automatically process data, assess structural condition, & signal need for maintenance actions



NDI vs. SHM & Typical Aircraft Flaws

Nondestructive Inspection (NDI) – examination of a material to damage/composition using methods that do not affect its future usefulness; focused, human interaction; requires access to area

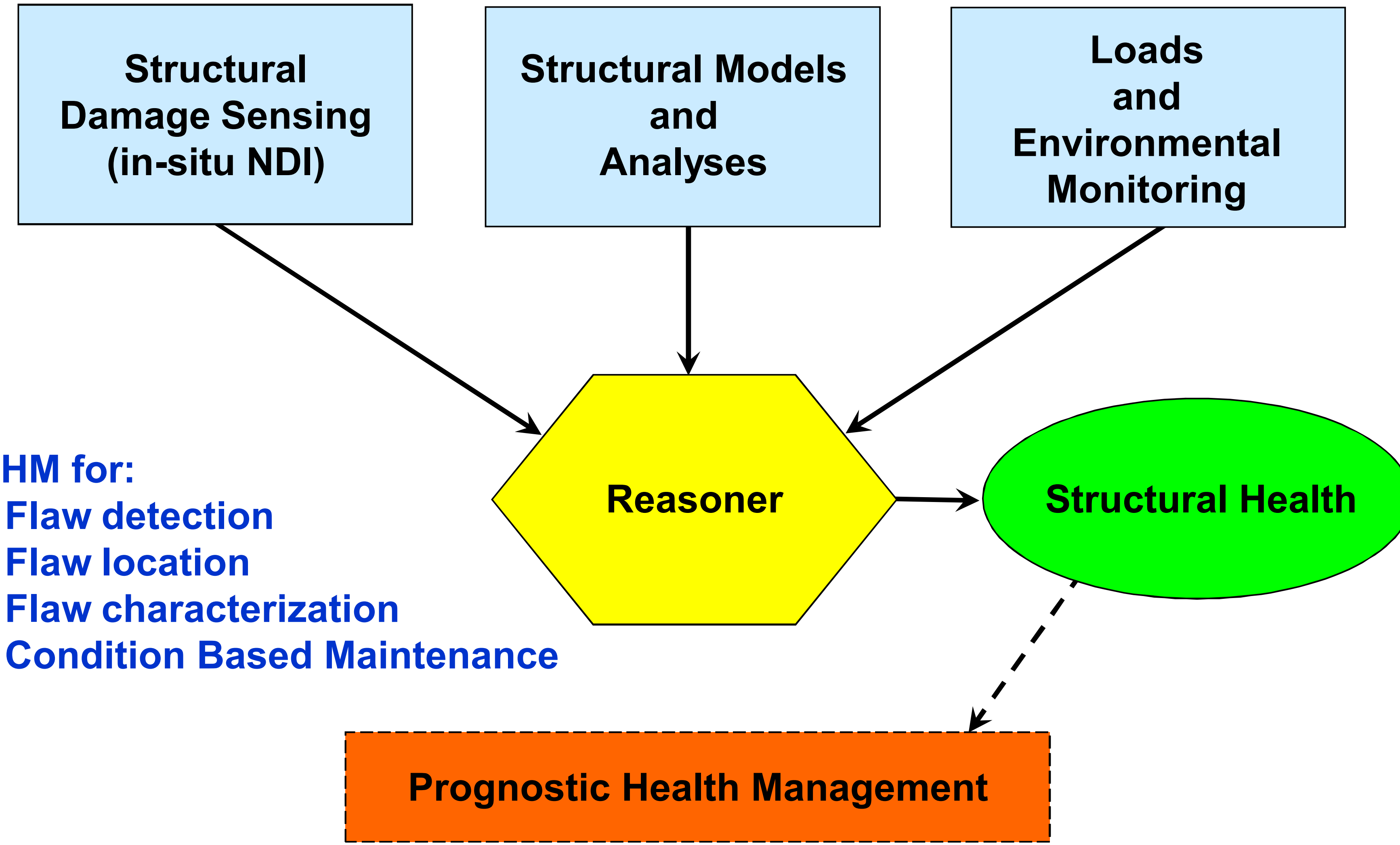
Structural Health Monitoring (SHM) – use of in-situ sensing to allow for rapid, remote, and real-time condition assessments (flaw detection); goal is to reduce operational costs and increase lifetime of structures


Substructure – Longeron Crack

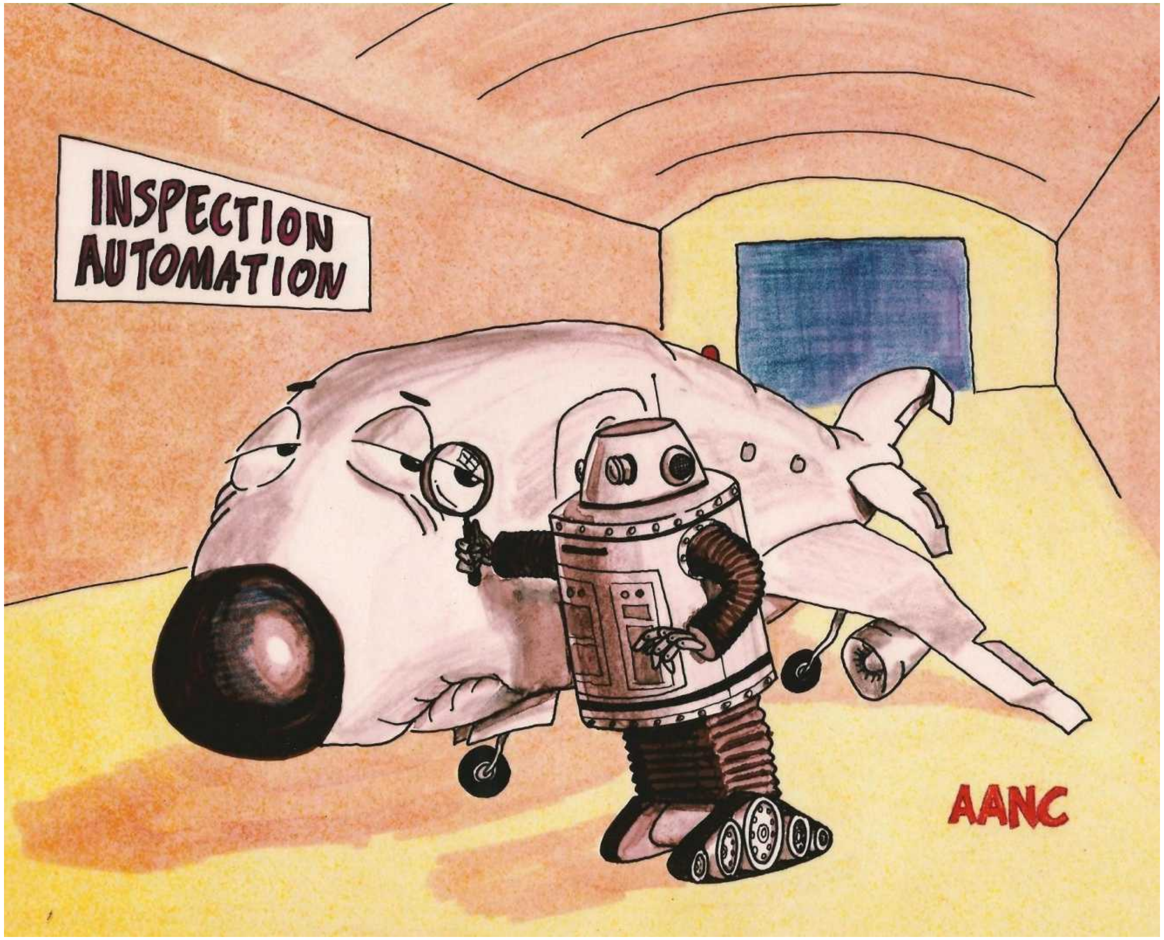

Composite Skin Disbonded from Honeycomb


Corrosion Around Riveted Joint

Structural Health Monitoring



SHM for:
- Flaw detection
- Flaw location
- Flaw characterization
- Condition Based Maintenance

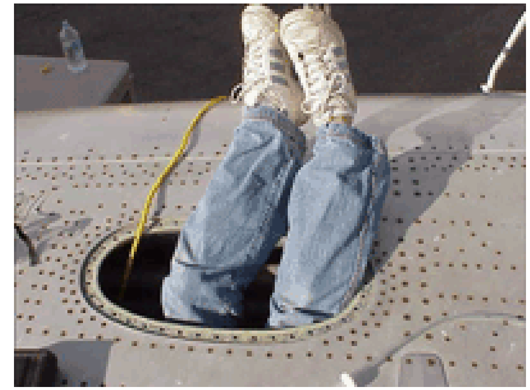


Definition is somewhat agreed upon. Usage and deployment covers a wide range of thoughts and options.

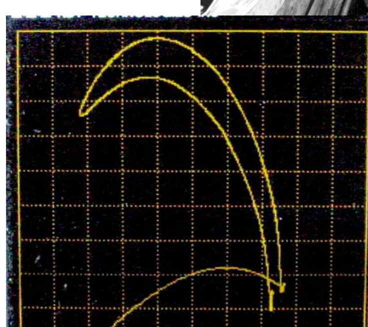
SHM Solutions & NDI Challenges

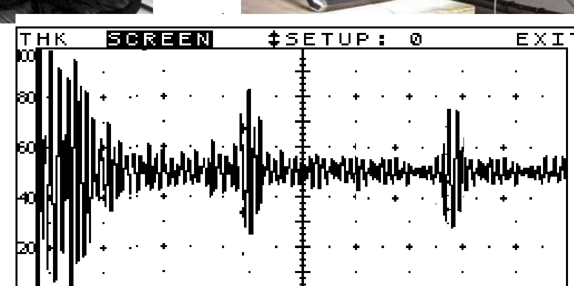
Difficulty in loads assignment, stress and fatigue calculations produces demands on NDI - **"You want me to find a flaw where, and how small??"**

Difficult Conditions

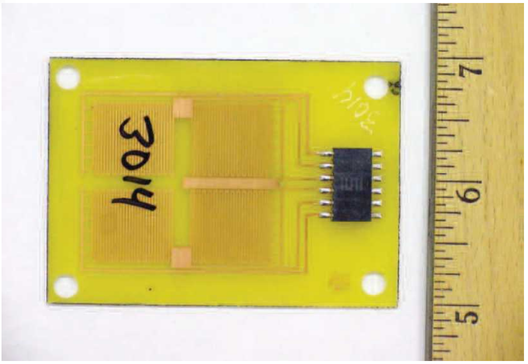


Lots of Rapid Data Interpretation

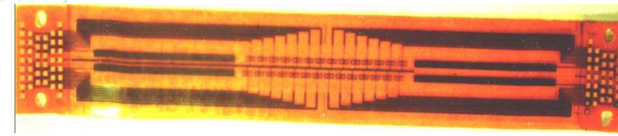




Sampling of SHM Sensors

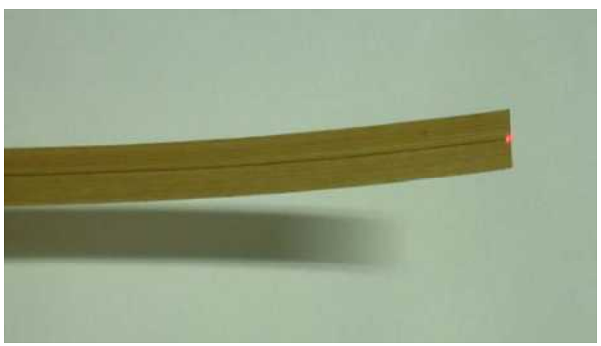


Cumulative Environmental Corrosion Sensor

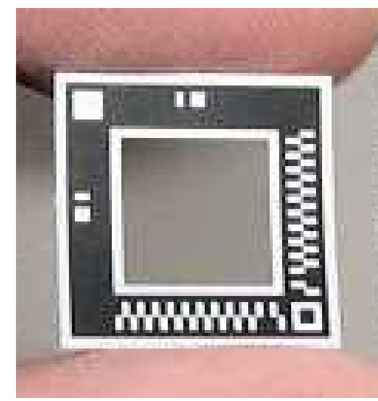


Flexible Eddy Current Array Probe

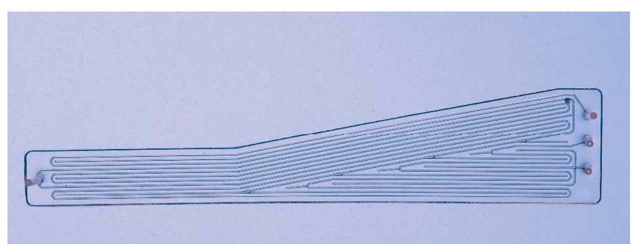
Vibro Fiber SHM Sensor



SMARTape Membrane Deformation Sensor



Direct Measurements Strain Sensor



Comparative Vacuum Monitoring Sensor

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

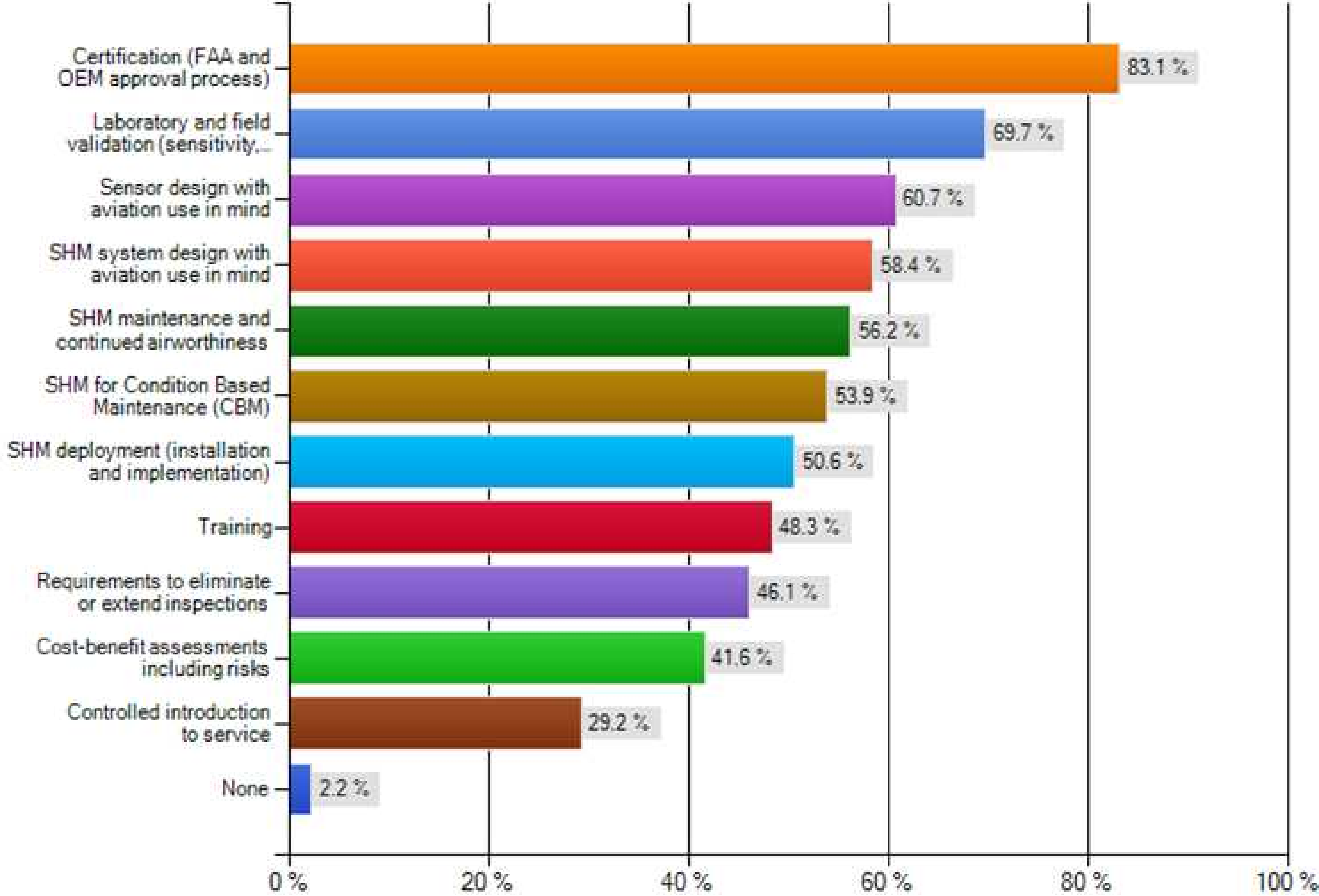
- Optimized structural efficiency
- New design philosophies (SHM designed into the structure)
- Weight savings
- Substitution of condition-based maintenance for current time-based maintenance practices

SHM Impediments & Challenges

Validation activities must address all issues !

- **Cost of sensors and sensor systems**
- **Ease of use and coverage area**
- **Need for rapid customization of sensors**
- **Need for substantial business case (cost-benefit analysis) – operators must realize benefits of multi-use**
- **OEMs may need to own technology**
- **Small-scale damage must be detected in large-scale structures**
- **Validation activities – general performance assessments needed; 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**
- **Technology transfer and implementation requires changes in maintenance programs**

Where do OEMs and Owners/Operators think Standardization and Guidelines are Needed and Feasible?



SHM Validation Considerations

- Declared Intent - application is for credit (replaces task or leads to changes in the requirements for a task); criticality describes the severity of the result of an SHM application failure or malfunction

- Usage Mode for SHM System
  - "Hot spot" or local monitoring (S-SHM)
  - Prognostic and condition-based health monitoring (P-SHM and C-SHM) - shift to predictive and continuous monitoring will require extensive validation and successful in-service experience so that regulatory agencies and operators can acquire confidence in these SHM approaches.

- Aircraft Maintenance Practices – change in programs; how to adopt

- Deployment – operational performance & repeatability

- Regulatory Actions and Industry Acceptance – depends on certification process (AMOC, NDT SPM, SB/AD, STC)

SHM Validation Considerations (cont.)

- **Key element in an SHM system is a calibration of sensor responses so that damage signatures can be clearly delineated from sensor data produced by undamaged structures**

- **Commercial implementation of SHM needs to be proven through statistically-viable lab performance data and successful field operation data**

- **Data requirements need to be established for determining the applicability of SHM (boundaries) and to address certification requirements.**

- **Educational initiatives with key players – understanding of SHM, its usage and its limitations**

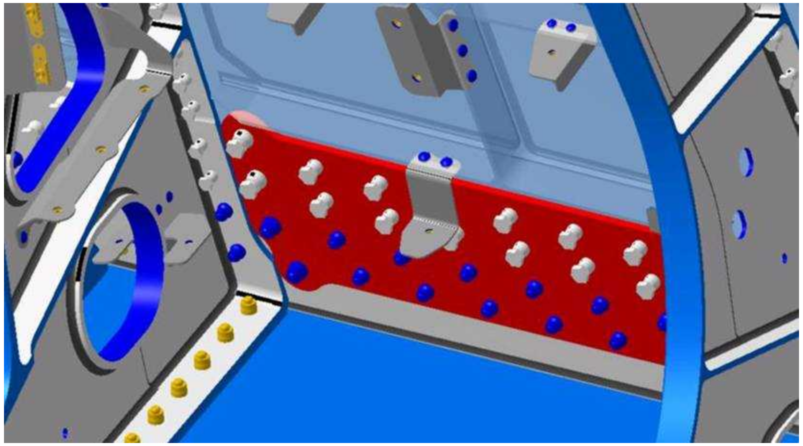
SHM Validation Process Tasks

- **Validation Process** should:
  1) provide a vehicle in which skills, instrument deployment & human error can be evaluated in an objective and quantitative manner
  2) provide an independent comparison between SHM solutions and alternate maintenance and monitoring methodologies
  3) optimize SHM utilization methodologies through a systematic evaluation of results obtained in laboratory and field test beds
  4) produce the necessary teaming between the airlines, aircraft manufacturers, regulators, and related SHM development and research agencies to ensure that all airworthiness concerns have been properly addressed.
- **Validation Assemblies** – assess technology and process; deployed under conditions identical to those of the day-to-day maintenance environment; use airline maintenance personnel who will perform the monitoring tasks using normal working practices and under normal working conditions
- **Comprehensive Evaluation** - Assess performance, training and integration into maintenance program (technical and admin)

SHM Validation Process Must Account for All Factors That Can Affect Performance

- **SHM Method** - SHM solution, device, sensor spacing, data acquisition process, data analysis method, data interpretation (thresholds, S/N), use of baselines
- **Structural Configuration** – geometry, material type, number of layers, fastener types and spacing, hole geometry, assembly specifics (fit/gaps), surface condition, coating changes
- **Flaw/Damage Condition** – type, X-Y location, depth, orientation, dimensions, morphology, presence of by-products
- **Environmental Conditions** – load scenario to generate damage, impact, environment to generate damage & establish durability

Complex Structure Requires Detailed SHM Validation

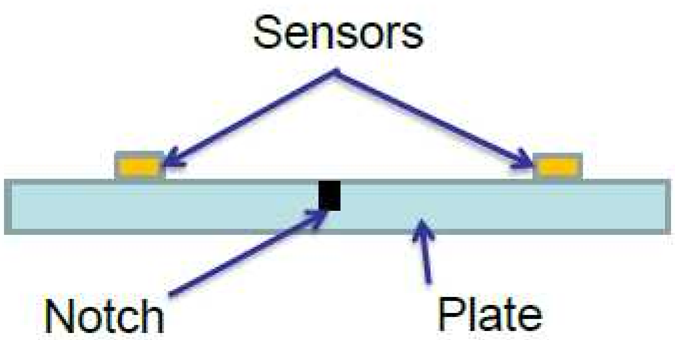


Summary of Potential SHM Evaluation Criteria

- **Accuracy** – POD and false calls
- **Sensitivity** – resolution, ID flaw type & severity
- **Analysis Capability** – presentation of data, clarity, remove subjectivity
- **Human Factors** – ease of use, compatibility with maintenance program
- **Versatility** – range of equipment use, depth of penetration, (re)calibration
- **Coverage and Scan Rate** – portability, set-up, area/second
- **Availability & Support** – history & stability of supplier
- **Cost** – cost-benefit analysis, multiple SHM applications needed
  - Sensor durability & failure rate
  - Data retention & link to baseline – time & coordination
  - SHM system sustainment
  - ROI time frame & global adoption of SHM

Validation with Representative Complexity

Required to translate laboratory success (performance assessment) to operational environment



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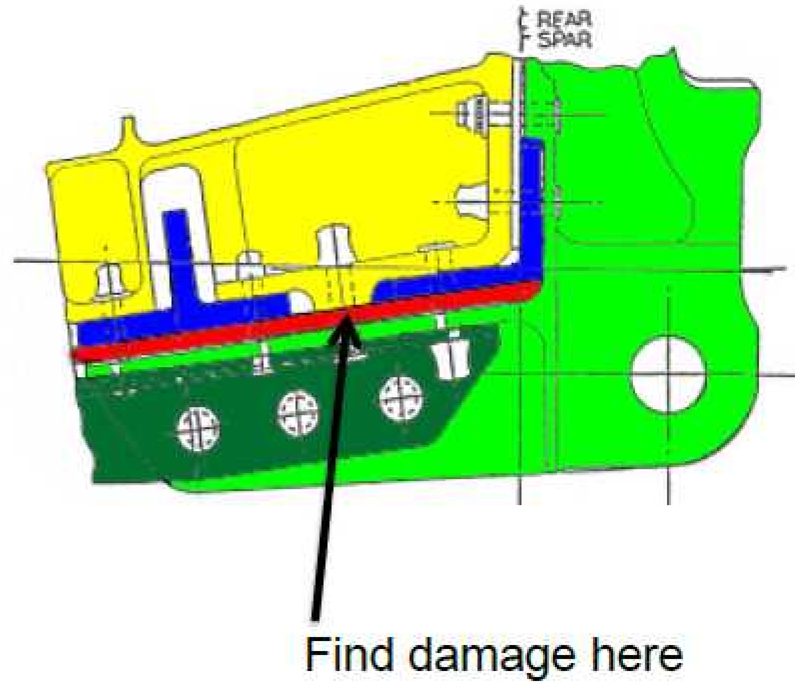


- Courtesy of Eric Lindgren, AFRL

FAA Regulatory Guidance & Aircraft Certification Process

- Use of SHM can be fostered through the addition of SHM solutions in FAA and OEM documents –
  - Federal Aviation Regulations (FARs),
  - Advisory Circulars (ACs)
  - Airworthiness Directives (ADs)
  - Service Bulletins (SBs)
  - Advisory and Rulemaking Committee Orders
  - Supplemental Type Certificate (STC) - issued by FAA to accommodate design mods; can be airline or someone other than holder of TC
  - Alternate Means of Compliance (AMOC)
  - Supplemental Structural Inspection Documents
- Validation requirements established by FAA, OEM, airline, and other agency teams – goals, usage and approach to be determined up front

Data Acquisition and Approval for SHM Use

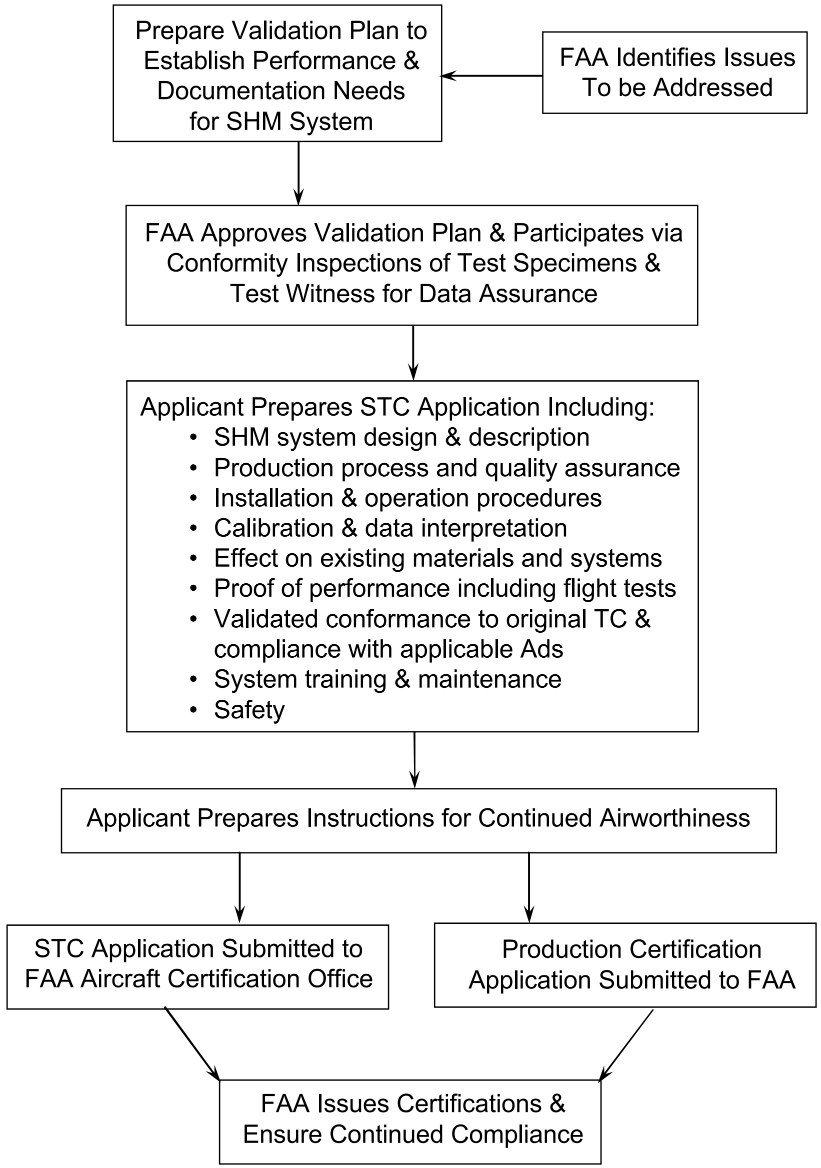
- Who is responsible for data integrity?
- How is data acquired and degree of oversight?
- What is flow of information?
- Procedures and Job Cards – uniform & repeatable process without need for oversight from SHM experts
- Define the role of OEM, airline, regulatory agency & other participants
- Administrative flow of documents & response needed from participants
- Use of "Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft" (ARP 6461) - Aerospace Industry Steering Committee on SHM

Approval for SHM Use – Sample Regulatory Process

Sample structure of validation process for regulatory approval (SB and AMOC) where OEM is the driver:

- **Part I: Validation Data Acquisition**
  - **OEM certification of data quality via DER/AR**
  - **Regulator issues Acceptance Letter for data**
  - **Regulatory agency kept informed and may participate**
  - **Test plan – specimen conformity & test witness**
- **Part II: Formal Interface with Regulatory Agency**
  - **Application to regulatory agency for SHM approval via a Design Change Application - certification plan addressing compliance with pertinent regulations (e.g. ACs); drawings; SBs; manual modifications**
  - **Submission of Document Package**
  - **Regulatory agency prepares Statement of Compliance – design change meets design limitations & continued airworthiness requirements**
- **Approval Letter Received from Regulatory Agency**

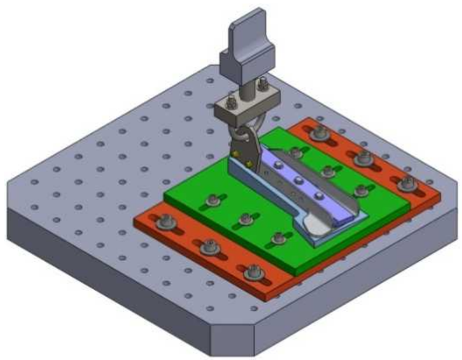
Sample Flow of an SHM System Through the Supplemental Type Certificate Process

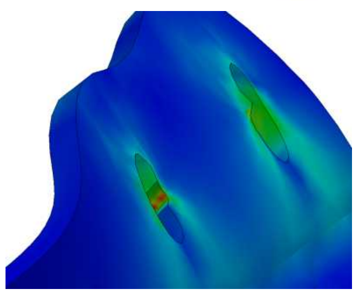


Validation of SHM Capability – Certification for Use

Laboratory Tests

- Quantify performance
- Env/durability
- POD – statistically relevant evaluation
- Reliability/repeatability





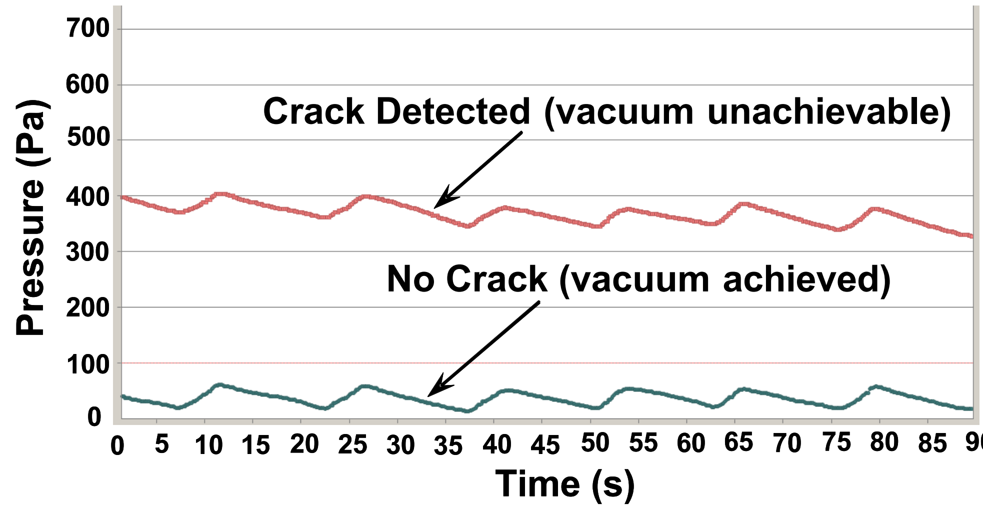
Flight Tests

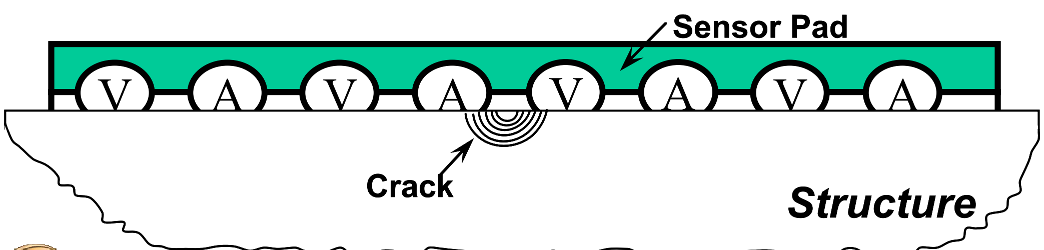
- Incomplete response statistics – lack of damage
- Deployed with airlines
- Need suite of monitoring data points (how many?, access to aircraft)
- Establish ability of current tech base to properly deploy SHM
- Establish ability of maintenance program to adopt SHM – admin obstacles

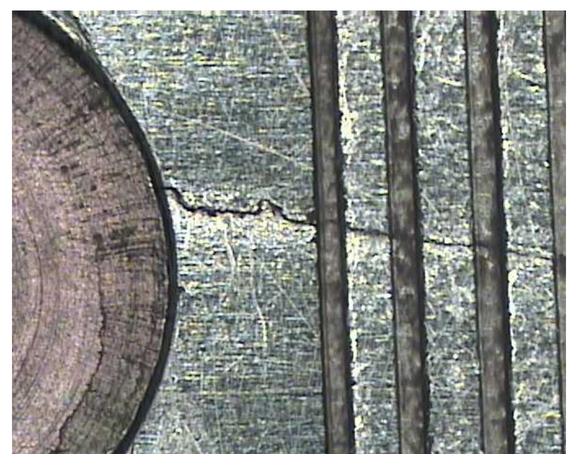
Comparative Vacuum Monitoring System

- **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



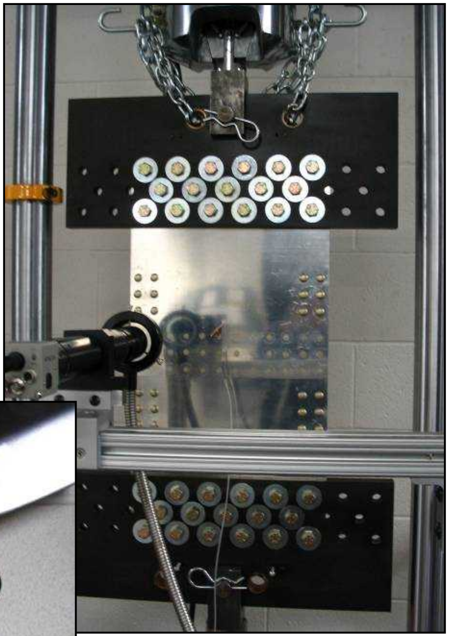




General Test Matrix to Quantify Probability of Crack Detection

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



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CVM Validation – Data Analysis Using One-Sided Tolerance Intervals

- **Data captured is crack length at CVM detection**
- **Reliability analysis – cumulative distribution function provides maximum likelihood estimation (POD)**
- **One-sided tolerance bound for various flaw sizes:**

$$POD_{95\%\ Confidence} = X \overline{+} (K_{n,\ 0.95,\ \alpha})\ (S)$$

X = Mean of detection lengths

K = Probability factor (~ sample size, confidence level)

S = Std. deviation of detection lengths

n = Sample size

1- α = Detection level

CVM Validation - Crack Detection Results

All POD levels listed are for 95% confidence

Description: 0.040 inch thick panel (primer surface)

PHASE 2 TESTS						
Panel	Fastener Crack Site	Distance from Fastener (inches)	Crack Length at CVM Detection (growth after install in inches)	SIM-8 Reading ∆Pa (Pasm)	PM-4 Read-out	PM-4 Indicate Crack (Y or N)
4018	5R	0.040	0.002	400-500	1607	Y
4018	6R	0.014	0.007	1700-1800	2847	Y
4018	7R	0.040	0.010	400-500	1704	Y
4018	5R(2)	0.050	0.009	1700-1800	2768	Y
4018	6L	0.052	0.004	1000-1100	2161	Y
407	7L	0.118	0.006	3758-3786	4790	Y
407	5L	0.125	0.010	654-695	1769	Y
407	7R	0.147	0.009	345-375	1426	Y
407	5R	0.139	0.011	374-409	1391	Y
4018	6L	0.194	0.007	530-560	1628	Y
4018	5L	0.253	0.006	380-430	1553	Y
4018	8R	0.262	0.011	320-360	1452	Y
407	6R	0.189	0.012	450-510	1661	Y

90% POD Level	False Calls
0.021"	0

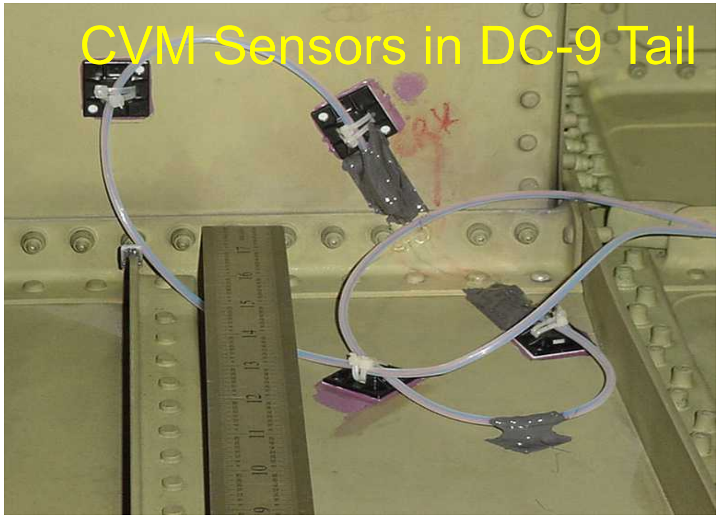
No false calls experienced in over 150 fatigue crack detection tests

[all panels are 2024-T3 alum. (AMS-4040, 41, QQ-A-250/5) with 0.0005" th. clad]

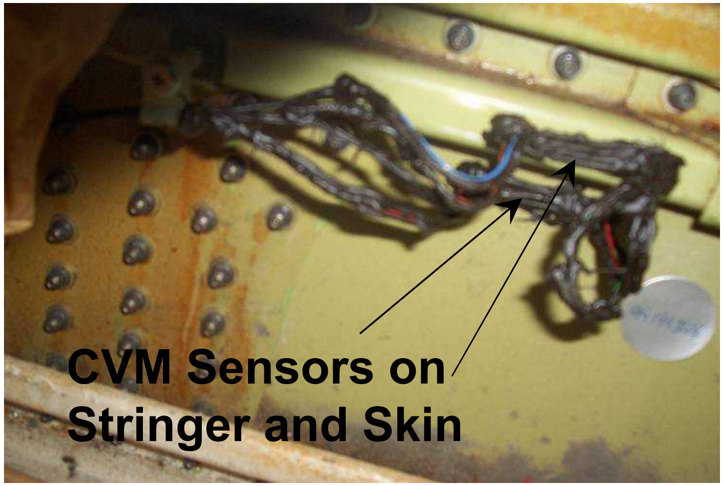
Field Evaluation of Sensor Applications

Environmental Durability Testing - To assess the long-term viability of CVM sensors in an actual operating environment, 22 sensors were installed on the following civil aircraft for functional evaluation:

Aircraft	Tail	Operator	Date	# Sensors	Status
DC-9	9961	NWA	Feb 04	6 (4 remaining)	2 sensors removed by NWA
DC-9	9968	NWA	Apr 05	6	3 sites
B757	669	Delta	Apr 05	8	4 sites in empennage on stringers, frames & near APB
B767	1811	Delta	Apr 05	6 (4 connected)	3 sites in empennage



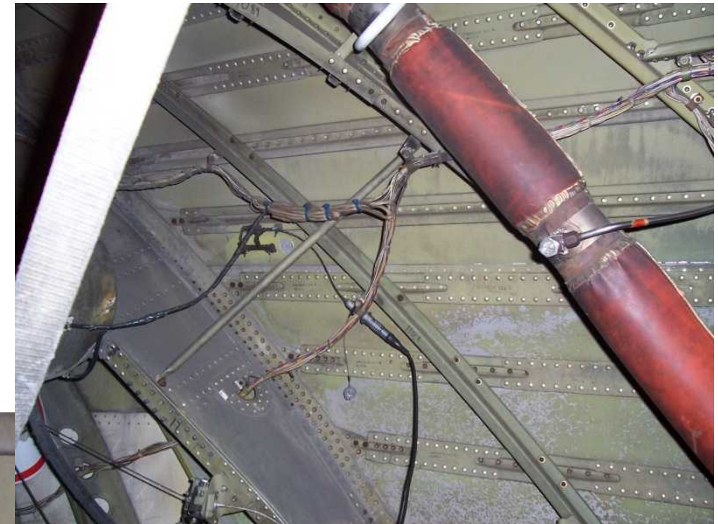
NWA Aft Baggage Compartment Sensor (A/C 9968)

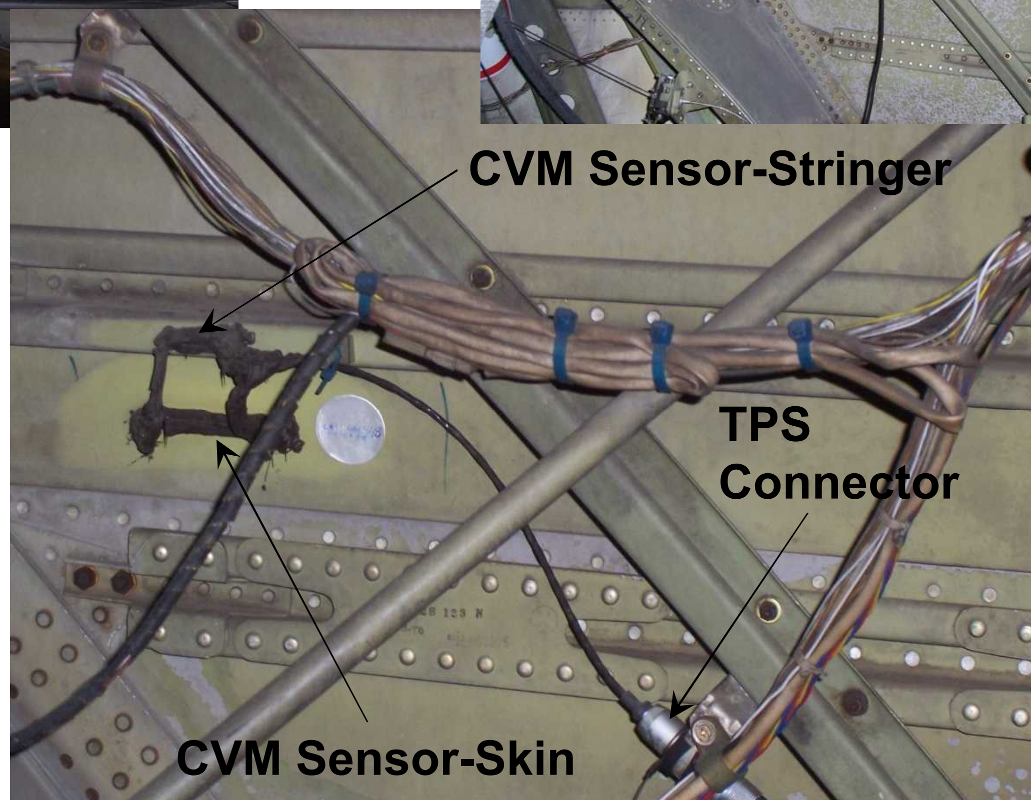


TPS connector routed to access panel

Monitoring CVM with PM-4 device

NWA Empennage Sensor (A/C 9968)

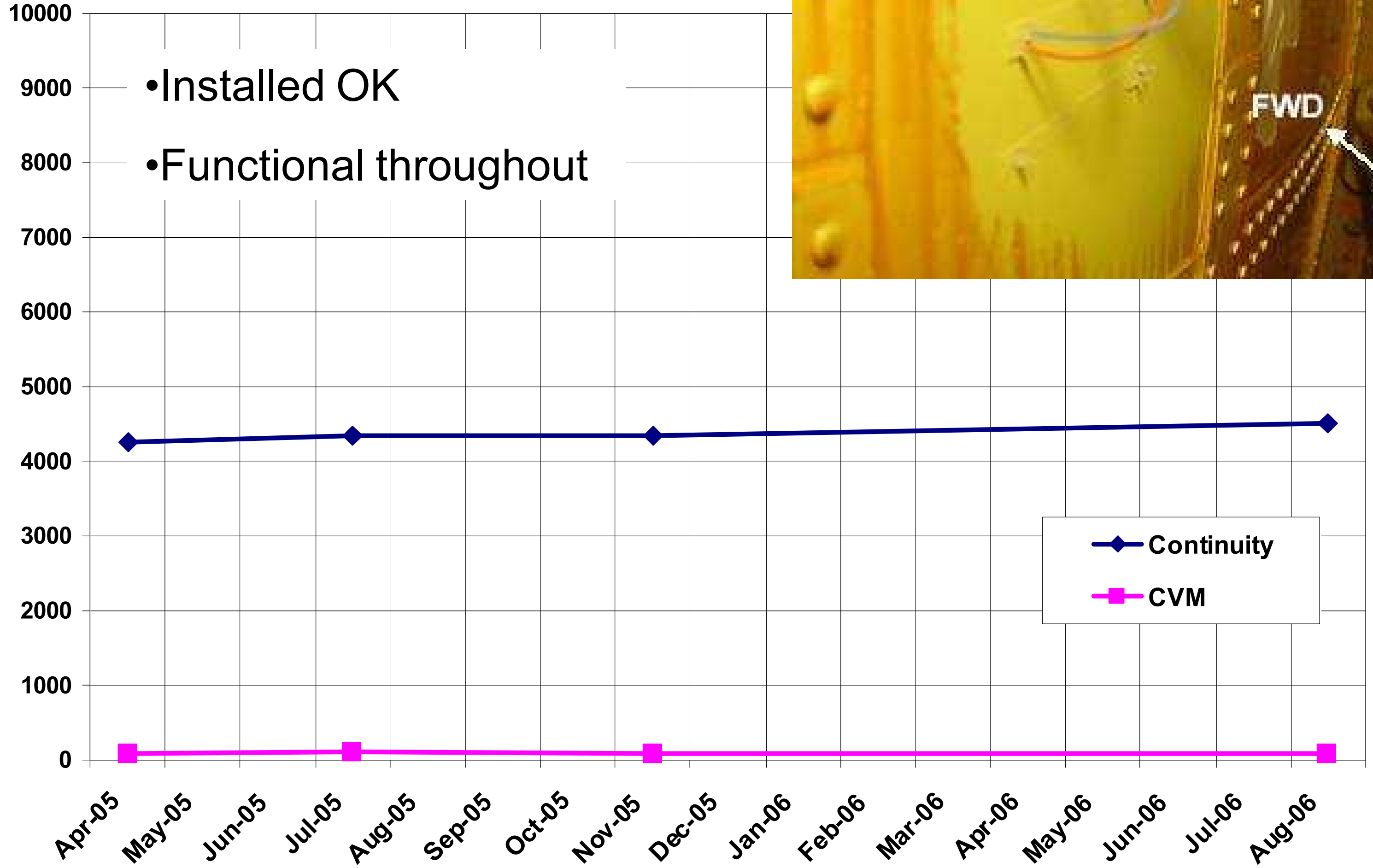




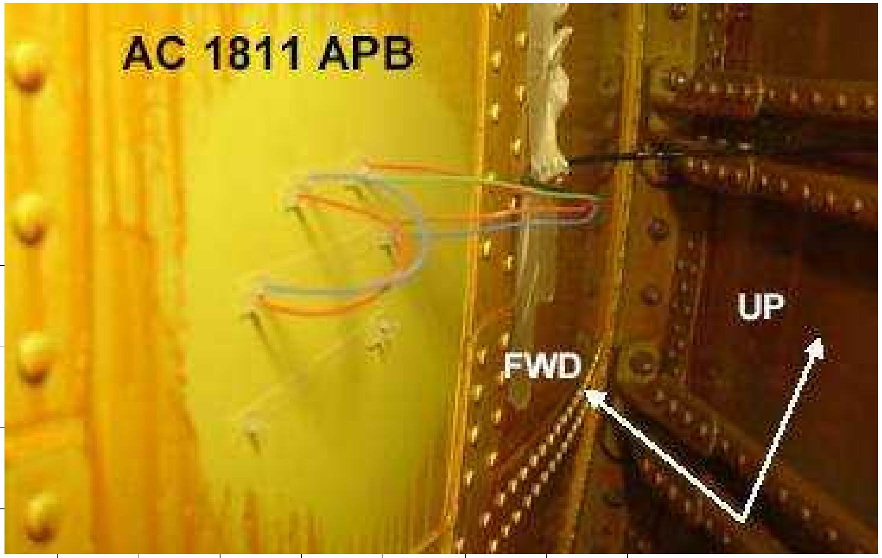
CVM Sensor Monitoring on Operational Aircraft

Delta - 767
Aft Pressure Bulkhead - Unpressurised
(AC1181)

Sensor Type 2



- Installed OK
- Functional throughout



Validation to Approve SHM Usage

- Strong interest in SHM – multitude of applications
- Industry's main concern with implementing SHM on aircraft is achieving a positive cost-benefit & time to obtain approval for SHM usage
- SHM should run in parallel with current NDI inspections for a period of time
- SHM performance – lab & multi-year flight test programs are needed
- SHM training and education - workshops
- AMOC & new SBs– safety driven use is achieved in concert with OEMS & regulatory agencies
- Approval through regulatory framework is the final formality to be addressed - standardization and guidelines are needed for certification and field validation

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