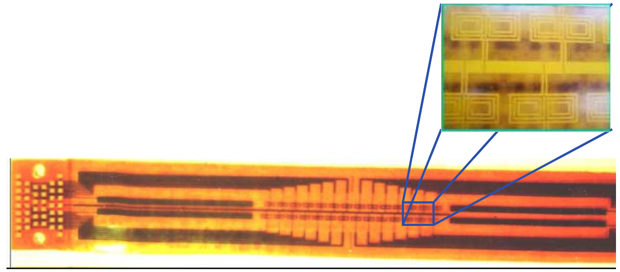
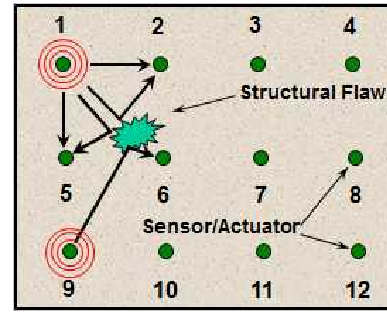
Automated Health Monitoring of Rail Cars and Railroad Bridges Using Embedded Sensors

SAND2016-9385C





Dennis Roach
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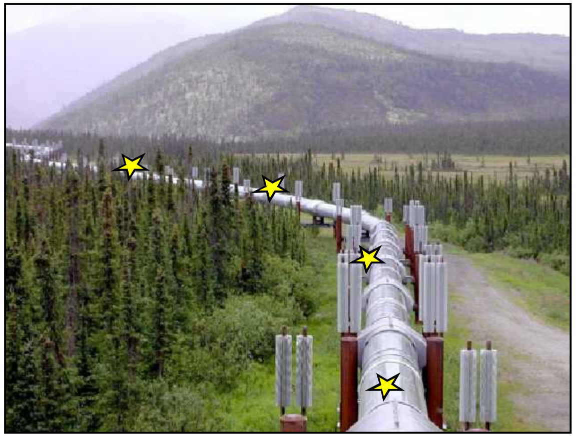
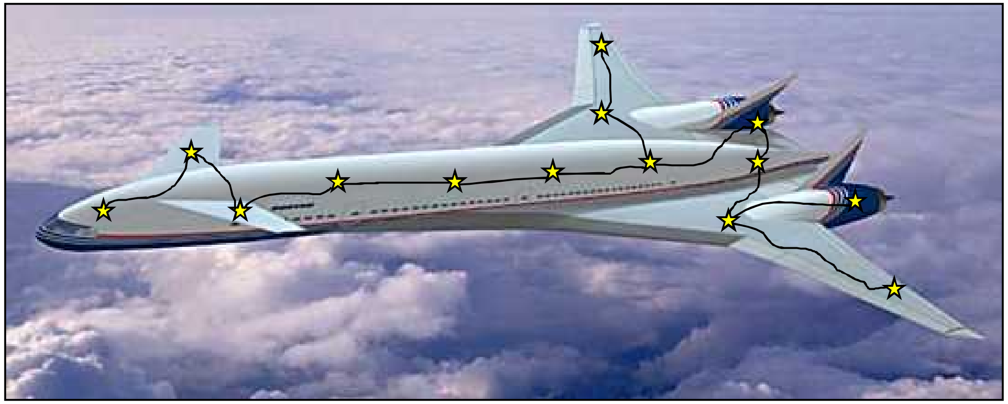
Distributed Sensor Networks for Structural Health Monitoring

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

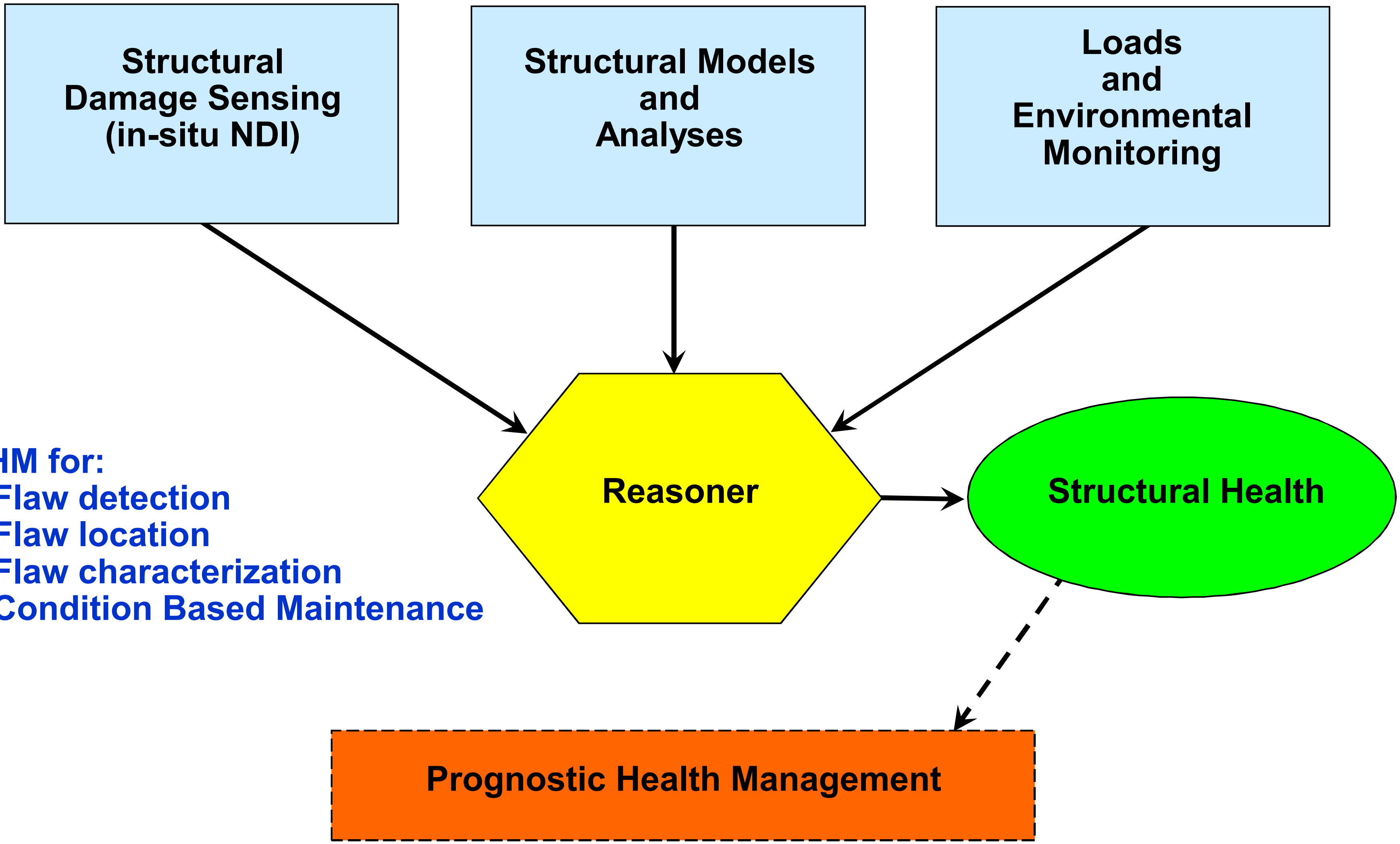


- Remotely monitored sensors allow for condition-based maintenance



- Automatically process data, assess structural condition & signal need for maintenance actions

Structural Health Monitoring



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

NDI vs. SHM – Definition

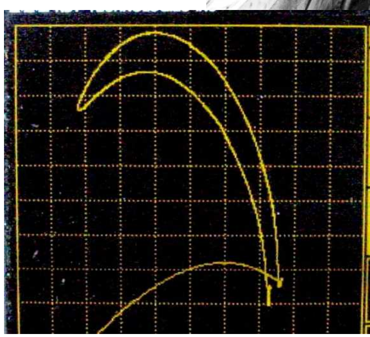
Nondestructive Inspection (NDI) – examination of a material to determine geometry, damage, or composition by using technology that does not affect its future usefulness

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

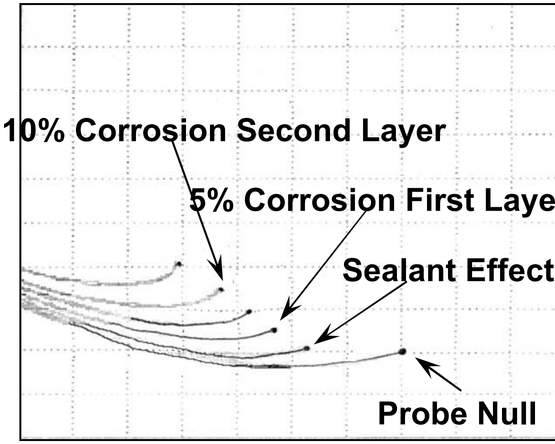
Structural Health Monitoring (SHM) – "Smart Structures;" use of NDI principles coupled with in-situ sensing to allow for rapid, remote, and real-time condition assessments (flaw detection); goal is to reduce operational costs and increase lifetime of structures & mechanisms

- 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

Typical A-Scan Signals Used for Flaw Detection with Hand-Held Devices

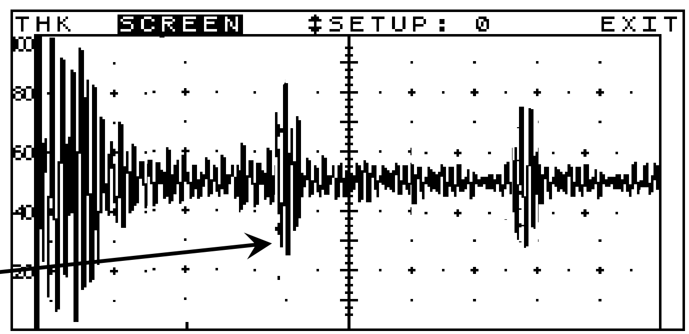


Eddy Current Signal at Crack Site



Corrosion Detection with Dual Frequency Eddy Current

Intermediate Echo Caused by Delamination



Ultrasonic Pitch-Catch UT Signals Comparing Flawed and Unflawed Signatures

Potential Benefits of SHM

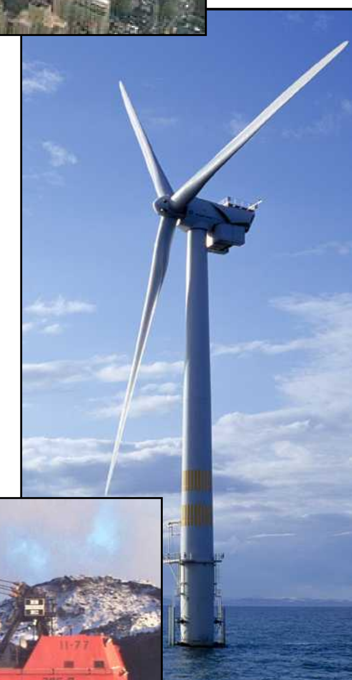
Near-Term

- Elimination of costly & potentially damaging structural disassembly
- Reduced operating and maintenance costs
- Detection of blunt impact events occurring during operation
- 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 – life extension

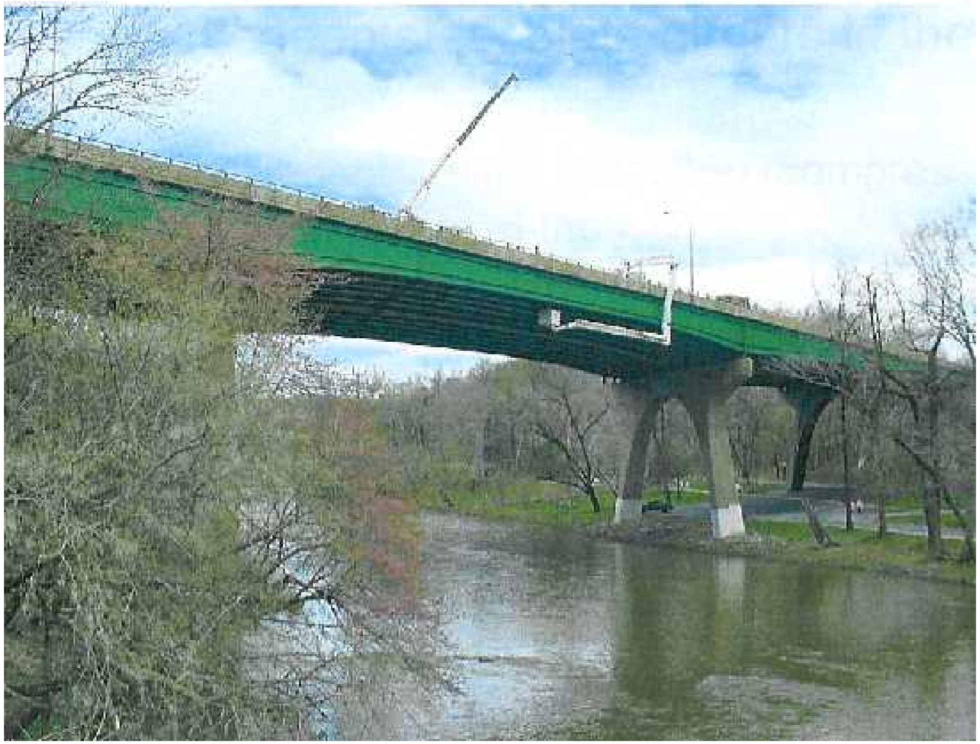
Long Term

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

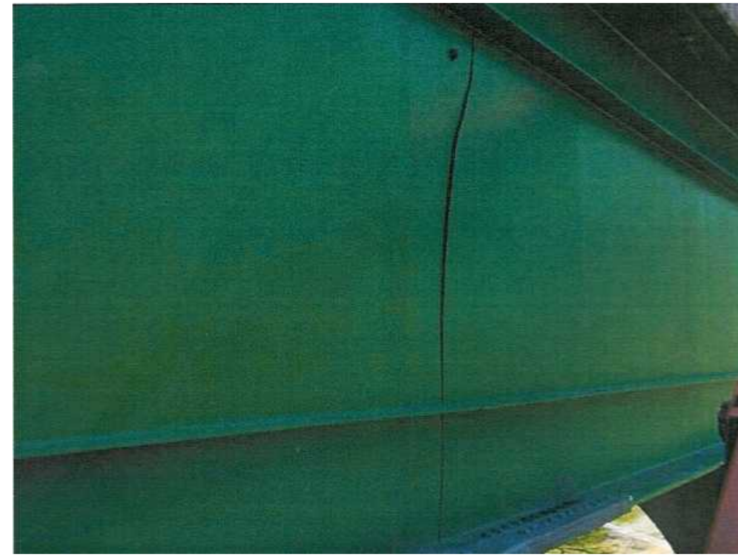
Wide Range of Uses for SHM Systems



Sample Bridge Damage



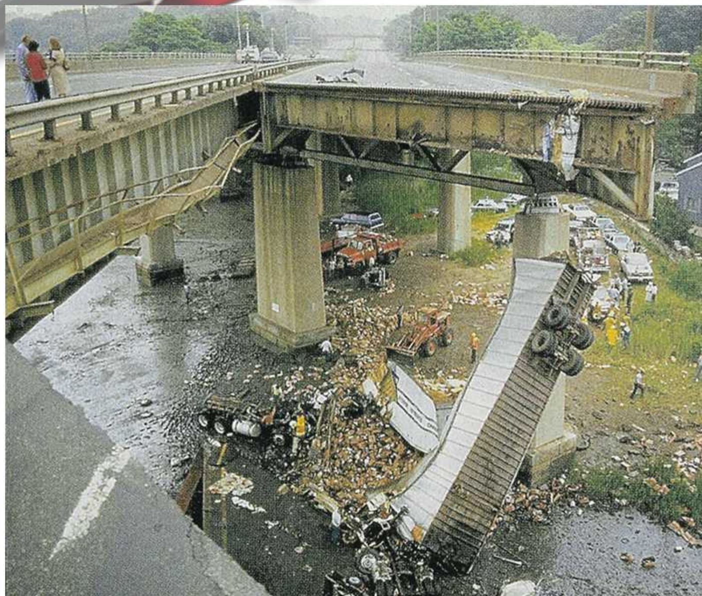
Brandywine River Bridge
Interstate Highway 95
Delaware



30% of 600,000 bridges in U.S. are listed as "structurally deficient" (Fed. Highway Admin. Nat. Bridge Inventory)

Majority of RR bridges in U.S. are operating beyond their initial design life

Sample Bridge Health Monitoring Needs



ASCE 2006 Report on U.S. Infrastructure (ranges from roads to hazardous-waste systems):

- Gives the country a grade of "D"
- Warns that "rotting" infrastructure poses risks to safety & economic growth
- Urges wholesale changes including increased R&D

"Even modest gains in the efficiency of construction and repair could yield huge overall savings."

-Tom Warne, Chairman
Transportation Research Board

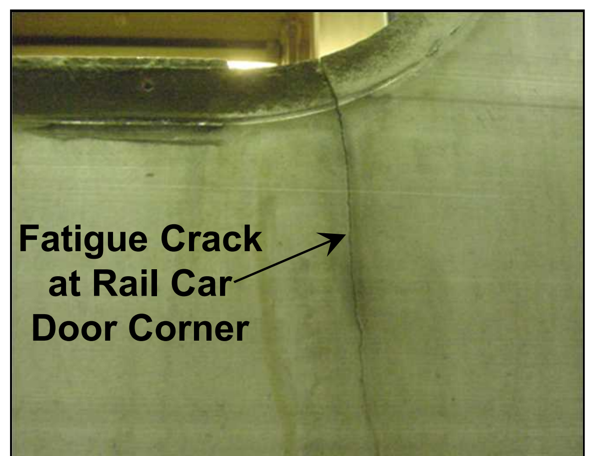
Sample Bridge & Rail Car Health Monitoring Needs

Many bridges are surpassing their initial design lifetime while budget restrictions limit or eliminate inspections.

Monitor Bridges – Interstate 35 Failure in USA

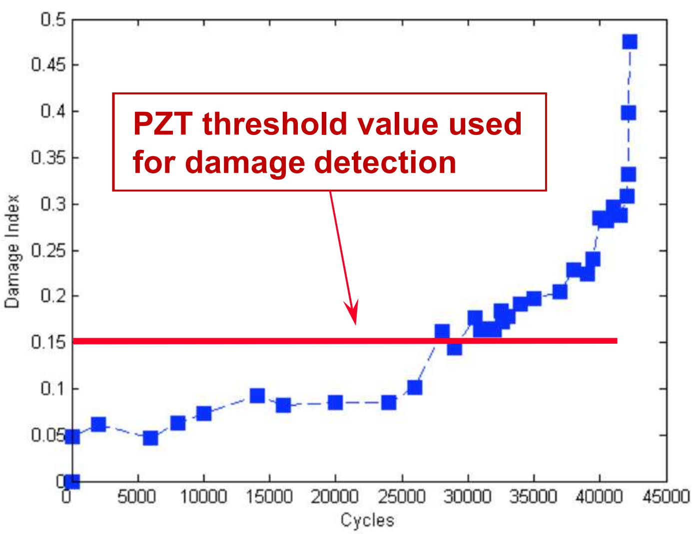
Collapse of Waegwan Railroad Bridge in S. Korea

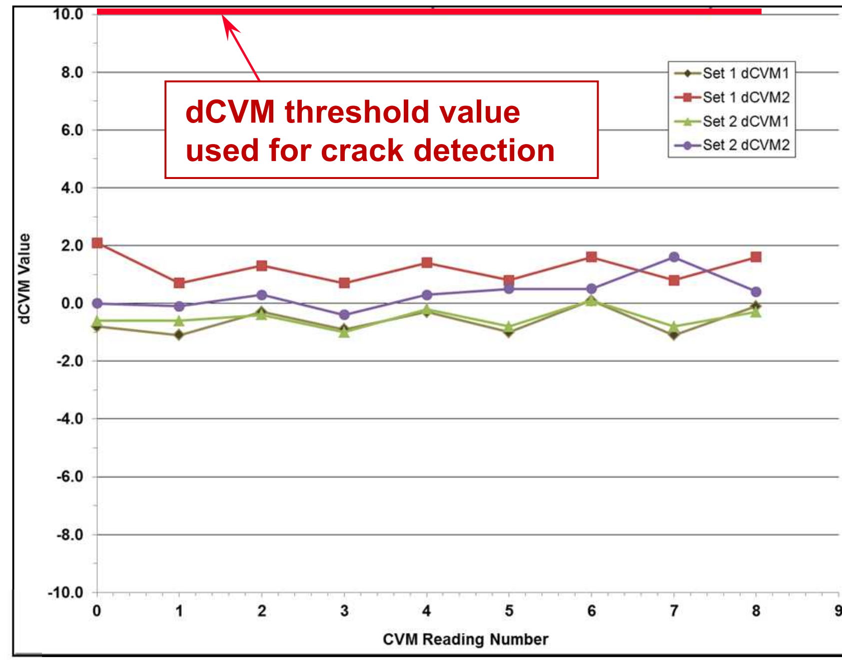
Rail Car from Washington DC Transit Authority

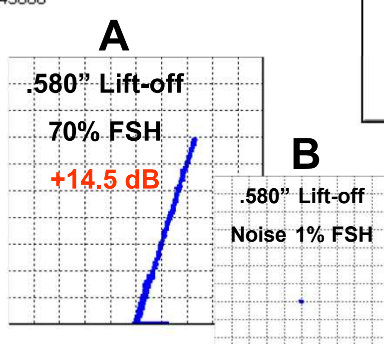


SHM Information – Minimize Intrepretation or Data Analysis

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



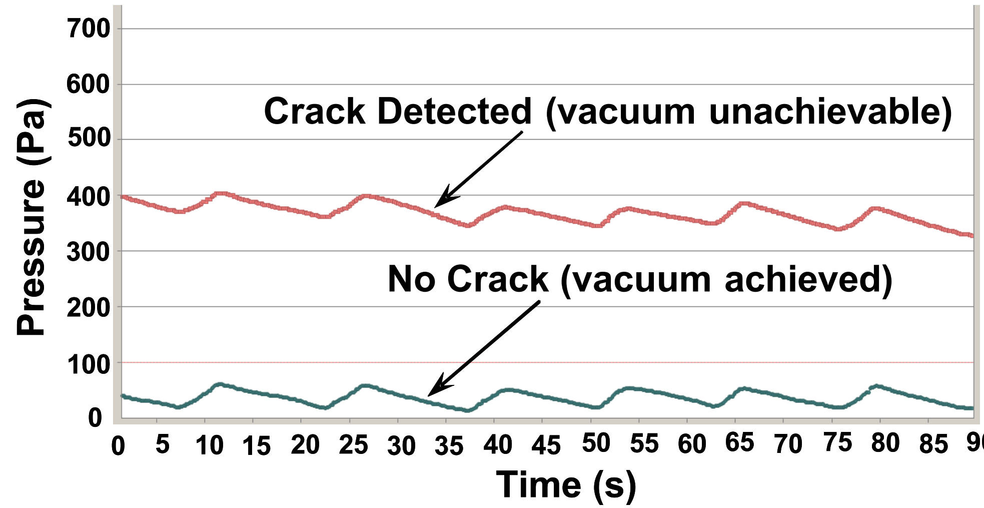




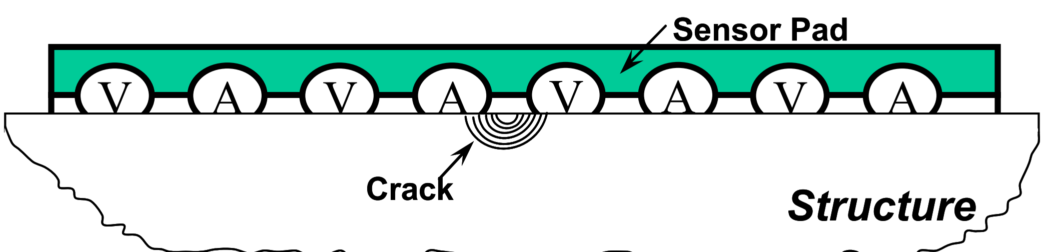
A = Sensor Response to Crack (flaw signal)
B = Sensor Response at Uncracked Region (signal noise)

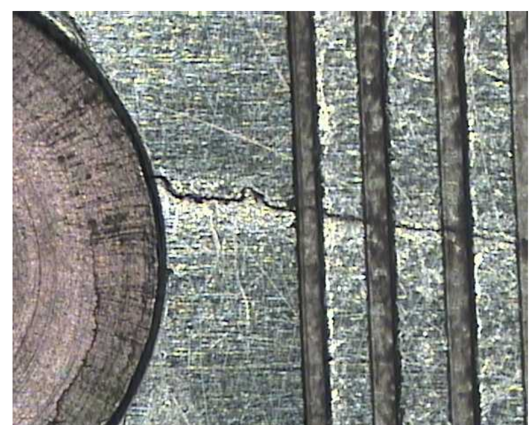
Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries
- Leakage path produces a measurable change in the vacuum level
- Doesn't require electrical excitation or couplant/contact



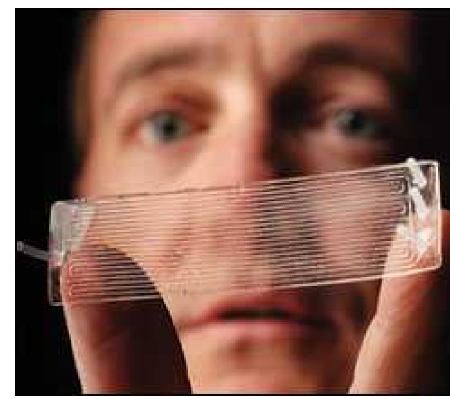
CVM Sensor Adjacent to Crack Initiation Site





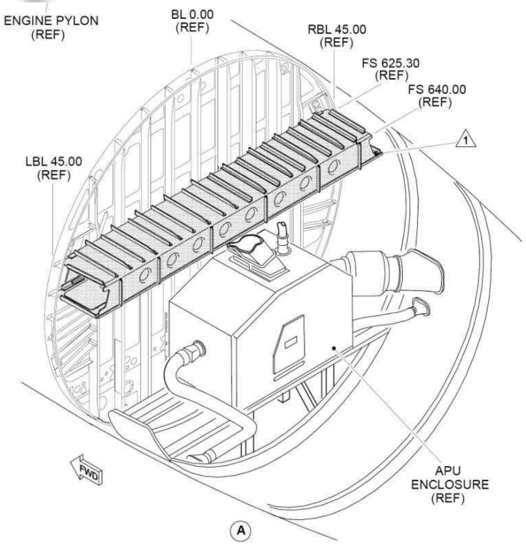
Drivers for Application of CVM Technology

- Overcome accessibility problems; sensors ducted to convenient access point
- Improve crack detection (easier & more often)
- Real-time information or more frequent, remote interrogation
- Initial focus – monitor known fatigue prone areas
- Long term possibilities – distributed systems; remotely monitored sensors allow for condition-based maintenance

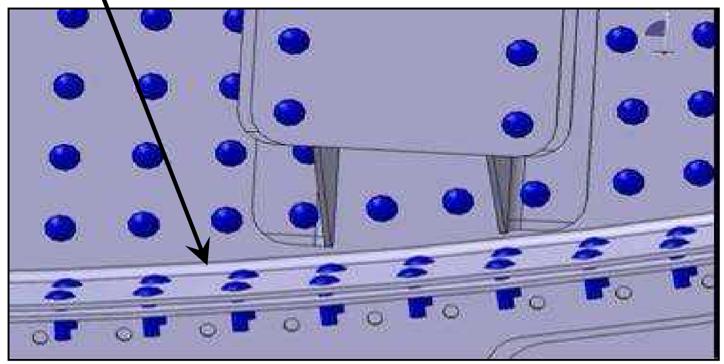


CVM Success on CRJ Aircraft

Pilot program with Bombardier and Air Canada



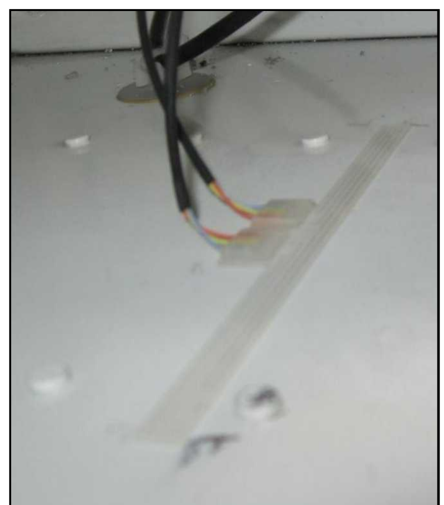
Inspect in the radius



Sensor Issues:

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

Aft Equipment Bay



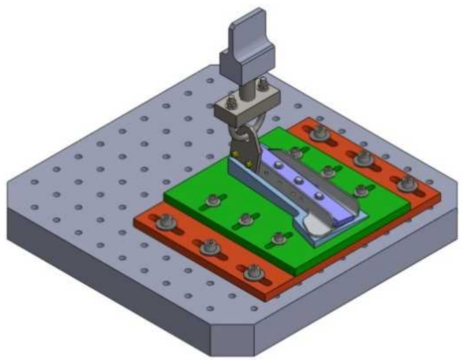
Validation of SHM Capability – Certification for Use

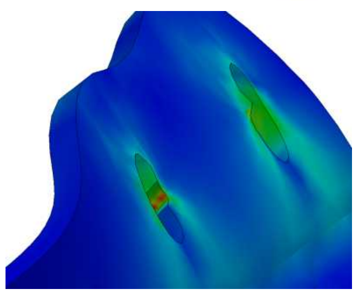
Laboratory Tests

- 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

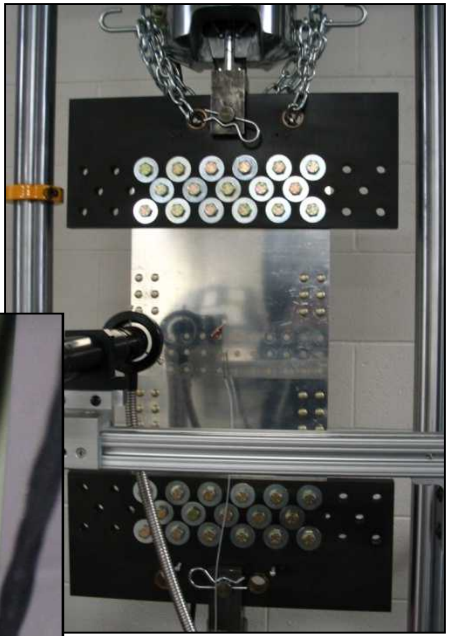


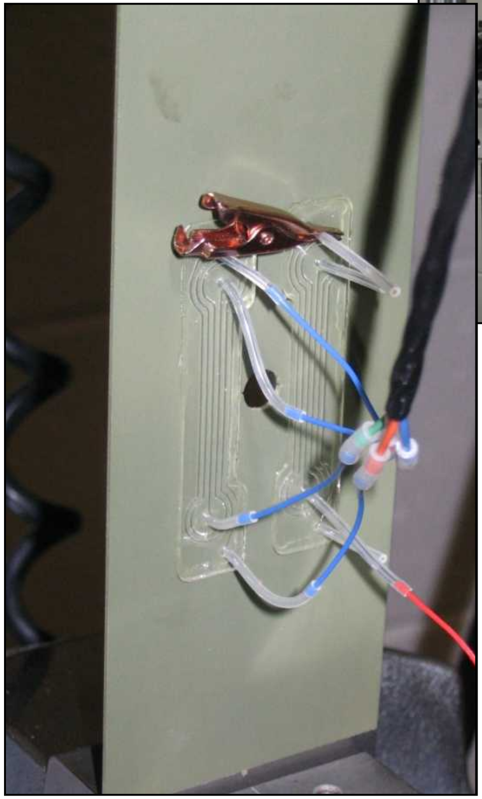


Test Matrix to Quantify Probability of Crack Detection

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





POD Assessment Using One-Sided Tolerance Interval

- Interval to cover a specified proportion of a population distributed with a given confidence – related to measures of process capability
- One-sided Tolerance Interval – estimates the upper bound which should contain a certain percentage of all measurements in the population with a specified confidence
- Since it is based on a sample of the entire population (n data points), confidence is less than 100%. Thus, it includes two proportions:
  - Percent coverage (90%)
  - Degree of confidence (95%)
- The reliability analysis becomes one of characterizing the distribution of flaw lengths and the cumulative distribution function is analogous to a Probability of Detection (POD) curve:

$$TI = X \pm (K_{n, \gamma, \alpha})(S) \qquad \text{[log scale calculation]}$$

- Interested in a 1-tailed interval (utilize “+” in equation); upper limit of TI. Uncertainty in knowing the true mean and population variance requires that the estimate of the range of values encompassing a given percentage of the population must increase to compensate.

CVM Validation – Data Analysis Using One-Sided Tolerance Intervals

- Crack detection based on PM-200 “Green Light” – “Red Light” results
- Data captured is the crack length at the time when CVM provided permanent (unloaded) detection
- Reliability analysis – cumulative distribution function provides maximum likelihood estimation (POD)
- One-sided tolerance bound for various flaw sizes:

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

X = Mean of detection lengths

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

S = Standard deviation of detection lengths

n = Sample size

α = Detection level

γ = Confidence level

POD Calculations - One-Sided Tolerance Interval

POD Determined from CVM Response Data

CVM Crack Detection Data (0.040" th)

Bare Metal		Over Primer	
Flaw size (inch)	Log (flaw size)	Flaw size (inch)	Log (flaw size)
0.003	-2.52	0.002	-2.70
0.007	-2.15	0.007	-2.15
0.002	-2.70	0.010	-2.00
0.030	-1.52	0.009	-2.05
0.009	-2.05	0.004	-2.40
0.005	-2.30	0.006	-2.22
0.004	-2.40	0.010	-2.00
0.002	-2.70	0.009	-2.05
0.014	-1.85	0.011	-1.96
0.005	-2.30	0.007	-2.15
0.013	-1.89		
0.032	-1.49		

Statistic Estimates on Log Scale

Statistic	Over Bare metal	Over Primer
Mean	-2.1566	-2.1679
Stnd deviation	0.40889	0.22809

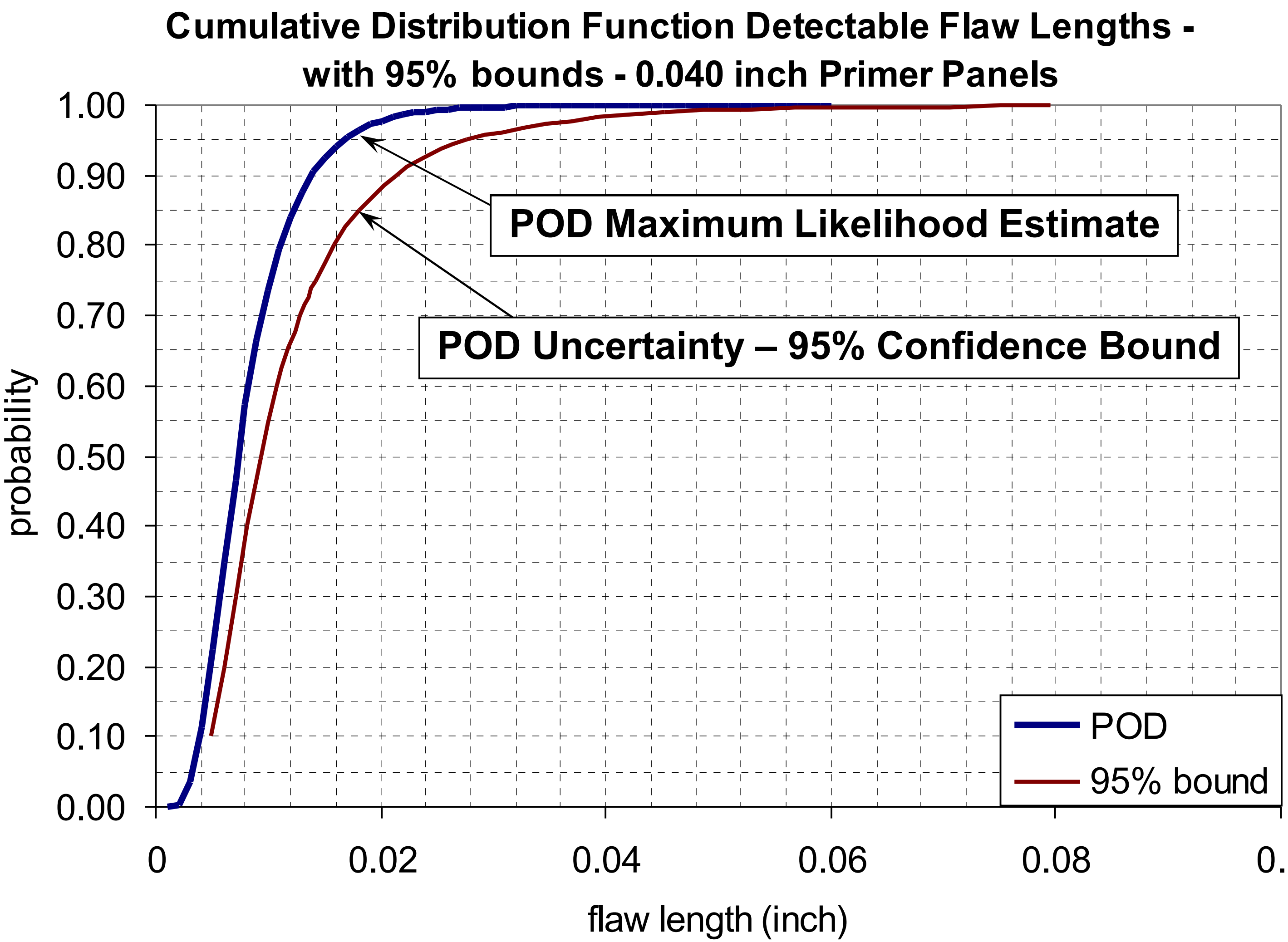
POD Detection Levels
(ɣ = 95%, n = 12 for bare, n=10 for primer)

Detection level $(1-\alpha)$	$K_{n,0.95,\alpha}$		$\bar{X} + K_{n,0.95,\alpha} \cdot S$ (log scale)		Flaw size in inches	
	bare	primer	bare	primer	bare	primer
0.75	1.366	1.465	-1.598	-1.834	0.025	0.015
0.90	2.210	2.355	-1.253	-1.631	0.056	0.023
0.95	2.736	2.911	-1.038	-1.504	0.092	0.031
0.99	3.747	3.981	-0.624	-1.260	0.237	0.055
0.999	4.900	5.203	-0.153	-0.981	0.703	0.104

$$\text{POD}_{\text{(Max Likelihood Est)}} = \frac{1}{xS\sqrt{2\pi}} EXP\left(\frac{-(ln(x)-\bar{X})^2}{2S^2}\right)$$

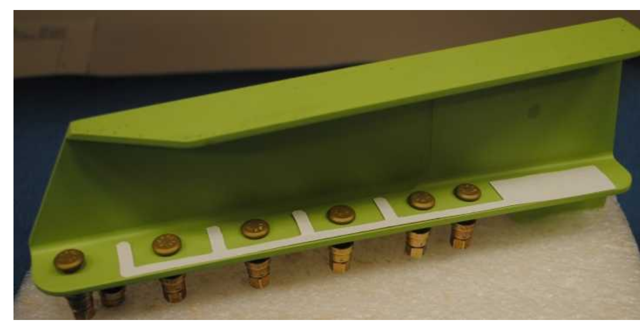
It is possible to calculate a one sided tolerance bound for various percentile flaw sizes - find factors $K_{n,\gamma,\alpha}$ to determine the confidence ɣ such that at least a proportion (α) of the distribution will be less than *X* + ($K_{n,\gamma,\alpha}$)S where *X* and *S* are estimators of the mean and the standard deviation computed from a random sample of size *n*

Sample Probability of Detection Curves for CVM

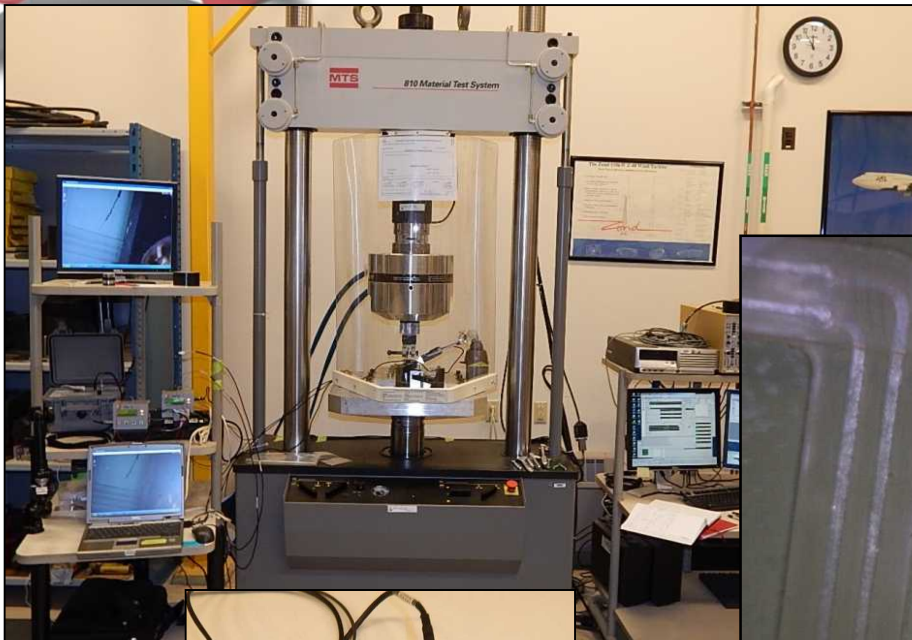


CVM Sensor Network Applied to 737 Wing Box Fittings

Alternate Means of Compliance with Current Visual Inspection Practice



737NG Center Wing Box – CVM Performance Tests



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POD Calculations - One-Sided Tolerance Interval

POD Determined from CVM Response Data on Wing Box Fitting

CVM Crack Detection Data

Eddy Current Crack Length at CVM (In)	Log of Crack Length at CVM Detection a (In)
0.215	-0.66756154
0.193	-0.714442691
0.193	-0.714442691
0.205	-0.688246139
0.200	-0.698970004
0.243	-0.614393726
0.180	-0.744727495
0.205	-0.688246139
0.238	-0.623423043
0.240	-0.619788758
0.258	-0.588380294
0.218	-0.661543506
0.178	-0.749579998
0.175	-0.756961951
0.220	-0.657577319
0.198	-0.70333481
0.208	-0.681936665
0.193	-0.714442691
0.235	-0.628932138
0.183	-0.73754891

Statistic Estimates on Log Scale

Statistic	Value in Log Scale	Value in Linear Scale
Mean (X)	-0.682724025	0.209
Stnd Deviation (S)	0.049124663	0.023962471

POD Detection Levels
(ɣ = 95%, n = 20)

Flaw Size: POD = X + K(S)	0.258160667

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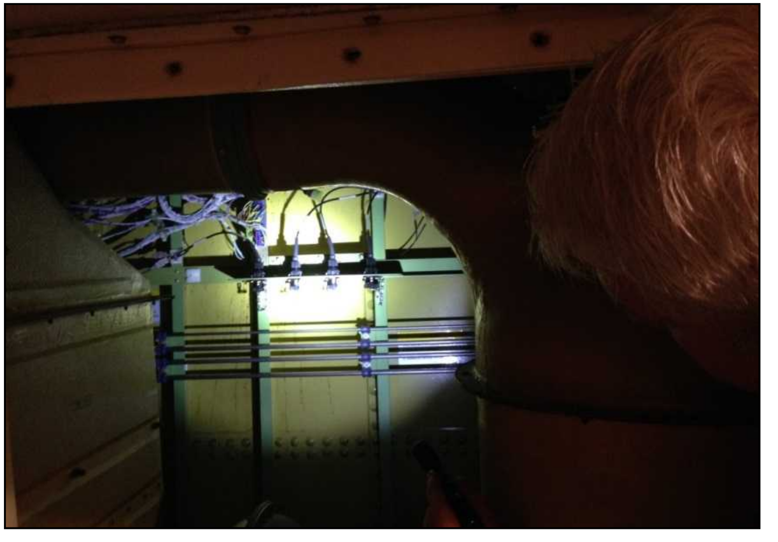
737NG Center Wing Box – Accumulating Successful Flight History

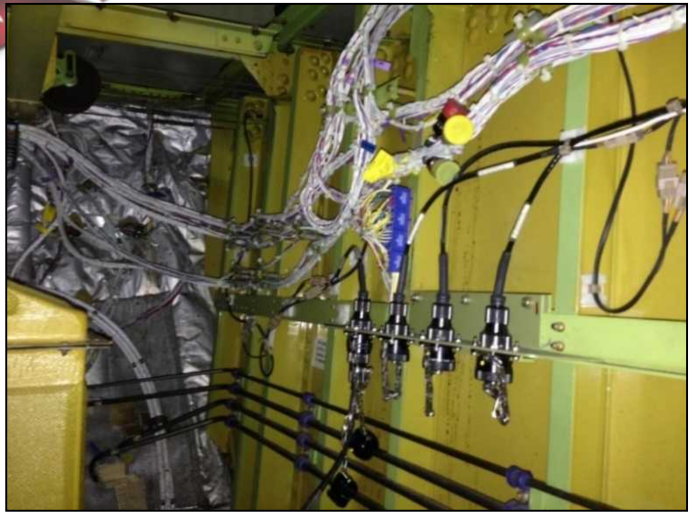
Aircraft Parked at Gate After Final Flight of the Day

Access to SLS Connectors Through Forward Baggage Compartment



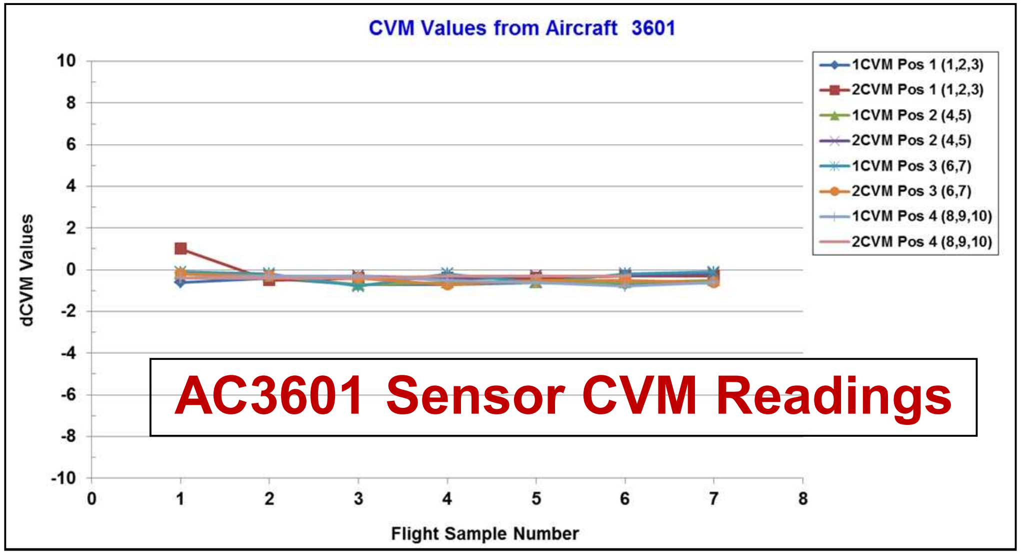
Removal of Baggage Liner to Access 4 SLS Connectors Mounted to Bulkhead

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



Syncrude Equipment Repair Applications

- Oil sand mining operation followed by mechanical and chemical processing to produce crude oil (260,000 barrels/day)
- Extreme fatigue, temperature, erosive, corrosive environments induce equipment damage
- Shutdowns to repair equipment can cost $1M per day
- CVM POD on thick steel structures = 0.5”

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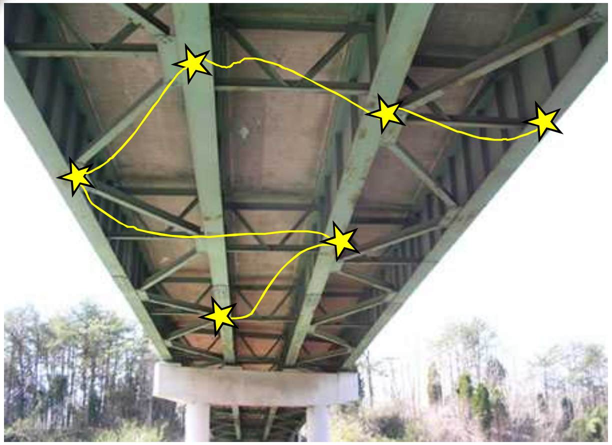
Real-Time Structural Health Monitoring Using Distributed CVM Sensor Networks



Real-Time, Remote Monitoring System for a Network of CVM Sensors

Validation of CVM Sensors for SHM Crack Detection

- Structural aging, combined with difficulties in monitoring widely-spaced infrastructure, produces a significant safety concern
- Real-time SHM systems can address these concerns by automating rapid, frequent structural assessments
- Early damage detection = less costly repairs
- CVM sensor detects cracks in the component it is adhered to – automated, remote diagnosis of a structure to avoid failure
- CVM sensors have been proven - multi-year lab performance assessment (sensitivity/POD and durability) & flight test programs have been completed
- Multiple successful aircraft applications - SHM Chapter in Boeing NDT Manual, Boeing Service Bulletin
- Proof-of-concept was successful on a thick, steel-member bridge and mining equipment
- Sensor networks can produce global SHM to assess performance of large structures

Automated Health Monitoring of Rail Cars and Railroad Bridges Using Embedded Sensors