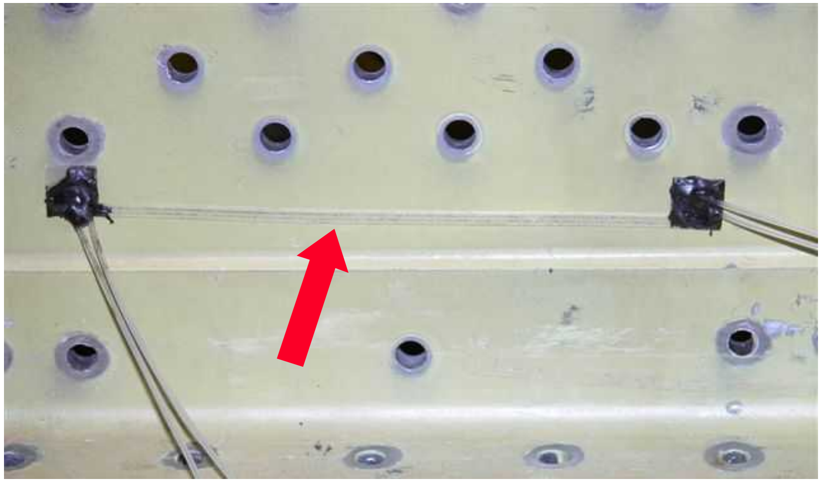
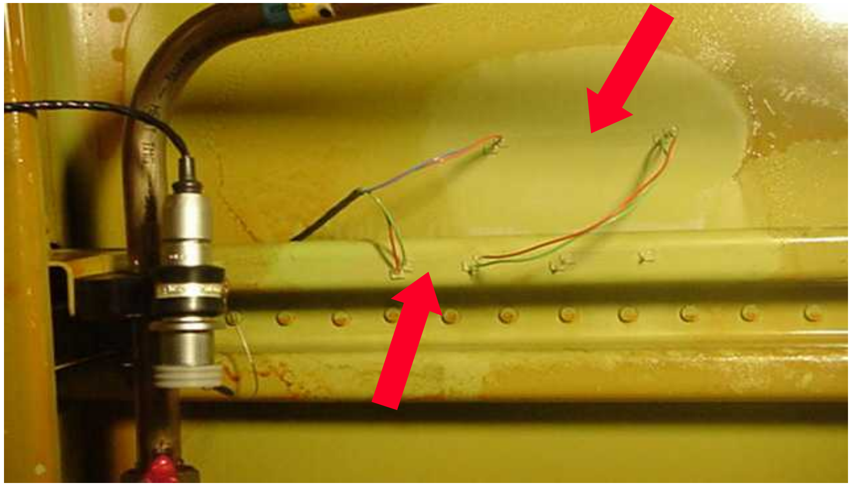
SAND2006-6406C

Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection





Dennis Roach, Jeff Kollgaard, Steve Emery, Jeff Register, Kyle Colavito, Dave Galella ….

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In-Situ Health Monitoring for Aircraft Using Comparative Vacuum Monitoring Sensors

TEAM MEMBERS

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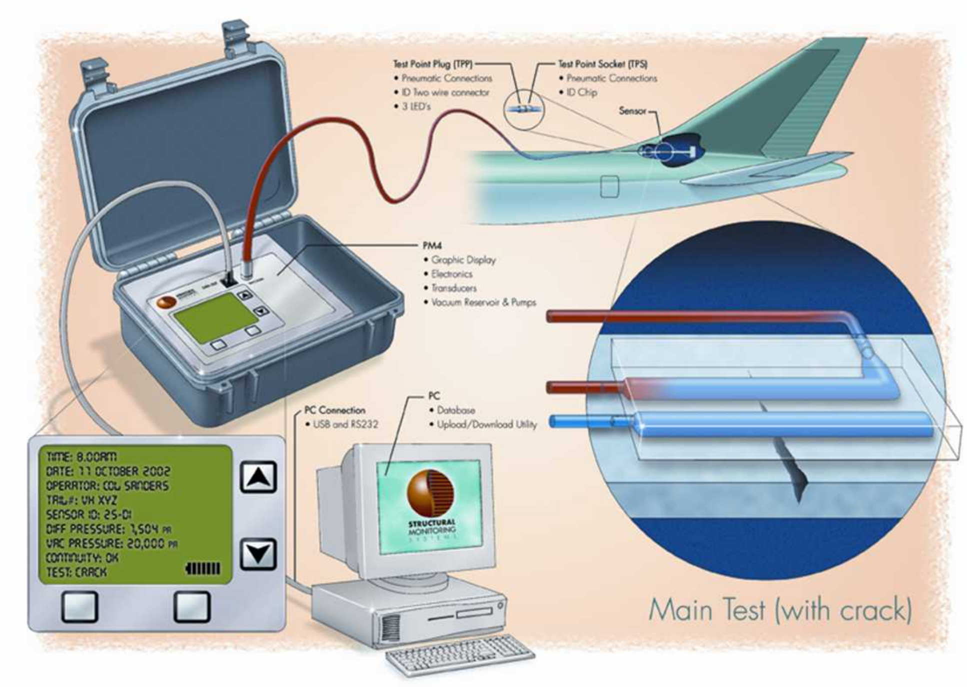
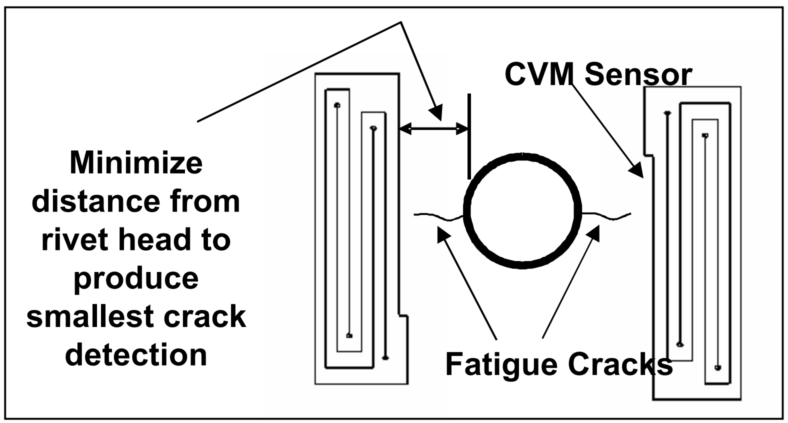
Drivers for Application of CVM Technology

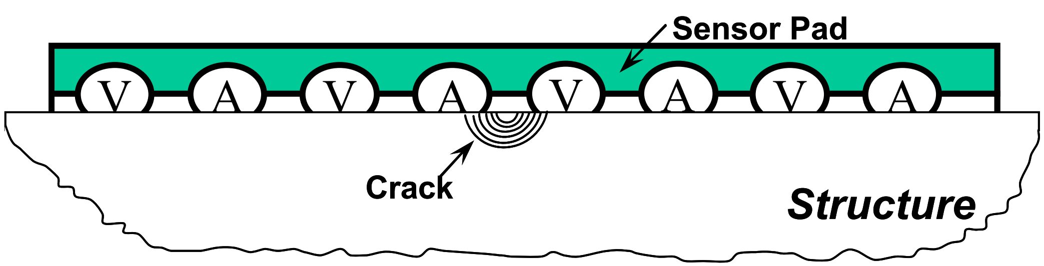
- Overcome accessibility problems; sensors ducted to convenient access point
- Improve crack detection
- Real-time information or more frequent, remote interrogation
- Initial focus – monitor know fatigue prone areas
- Long term possibilities – distributed systems; remotely monitored sensors allow for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

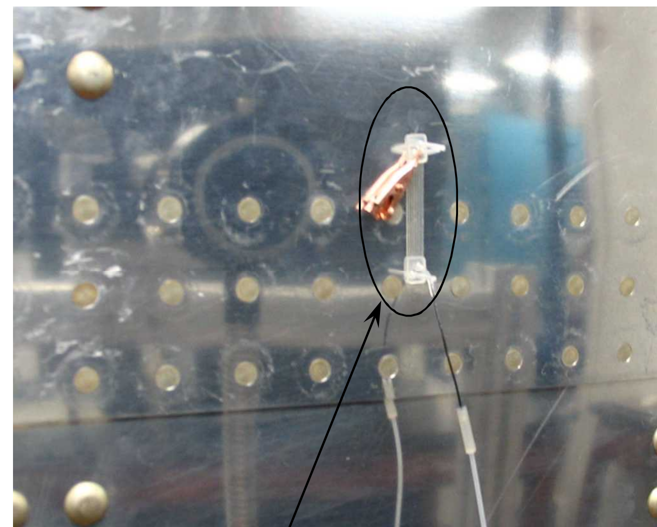


Comparative Vacuum Monitoring System

- **Sensors with fine channels on the adhesive face - applies a vacuum to a thin film sensor with embedded galleries open to the surface**
- **Leakage path between the atmospheric and vacuum galleries producing a measurable change in the vacuum level**
- **Doesn't require electrical excitation or couplant/contact**

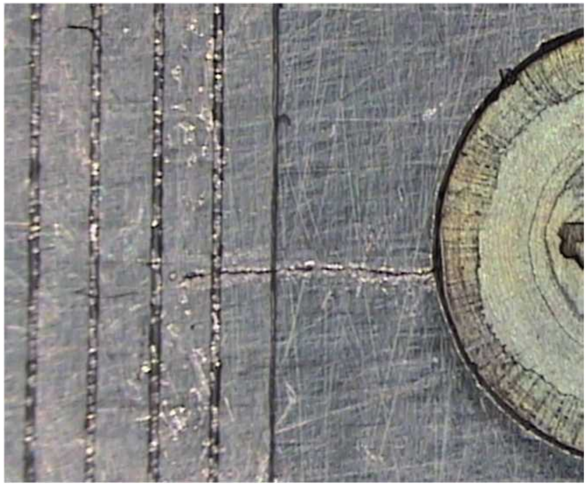


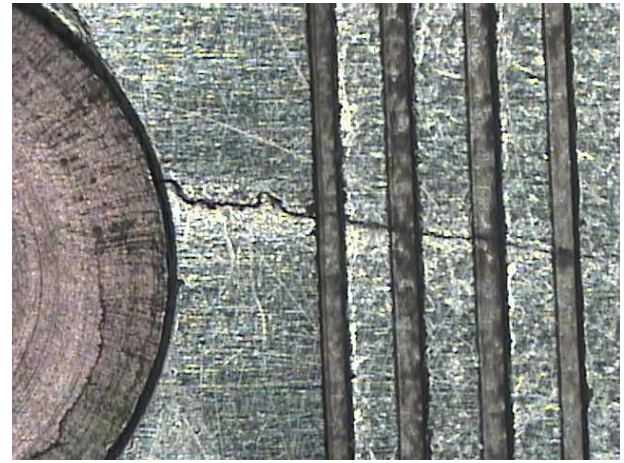


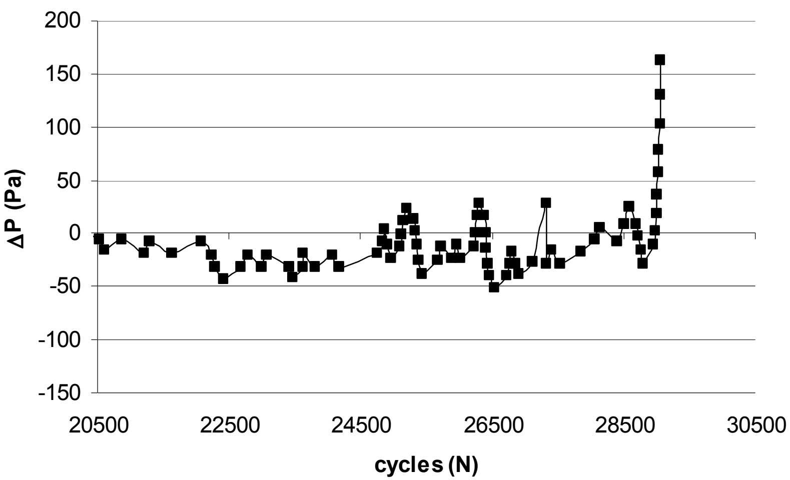


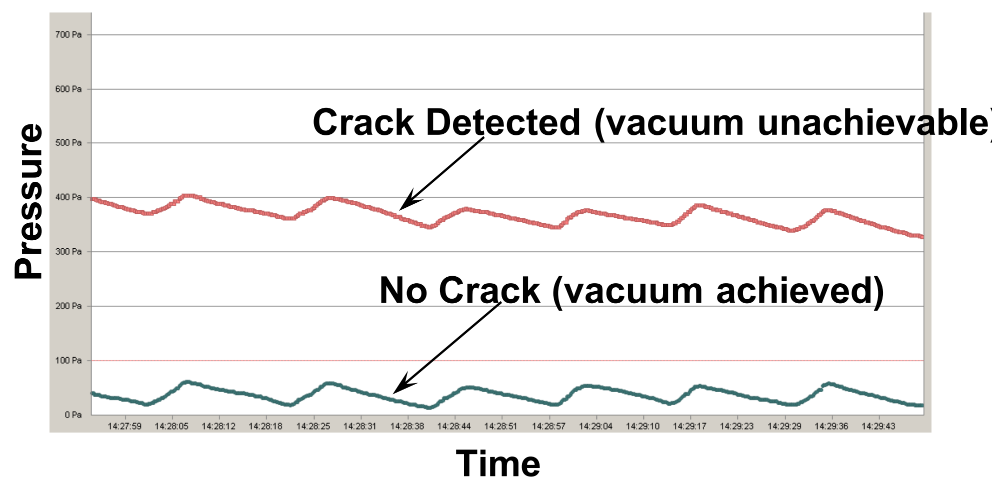
CVM Sensor Adjacent to Crack Initiation Site

Comparative Vacuum Monitoring System





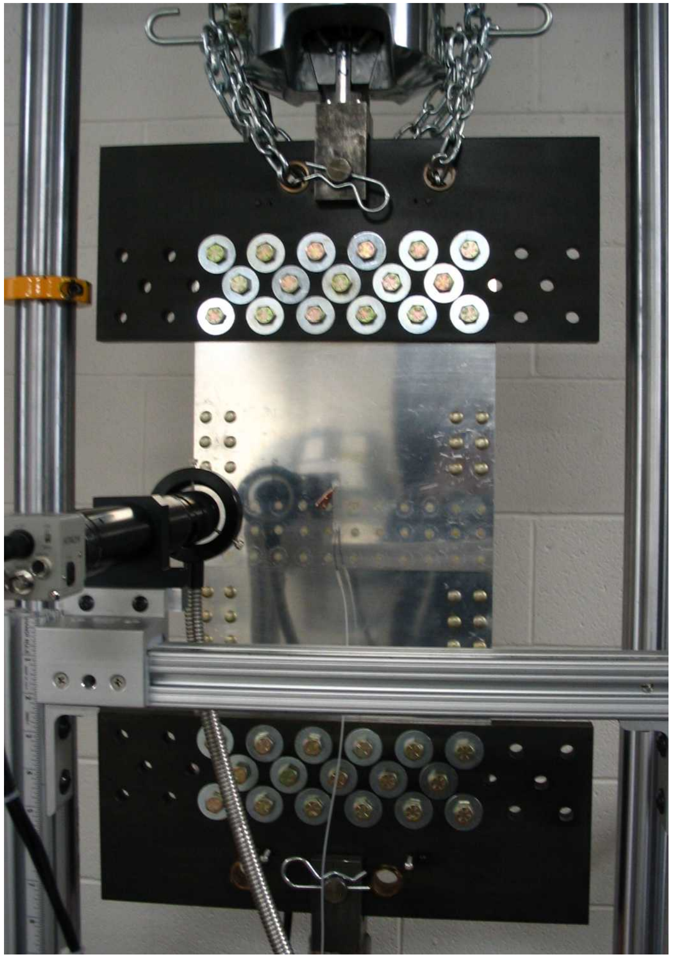




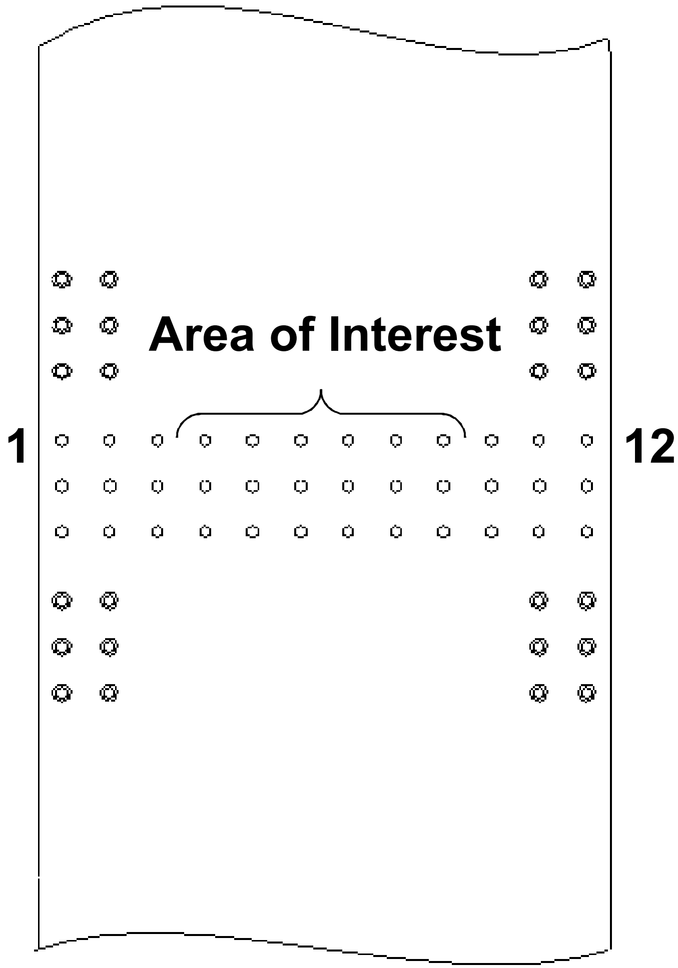
Test Matrix to Quantify Probability of Crack Detection

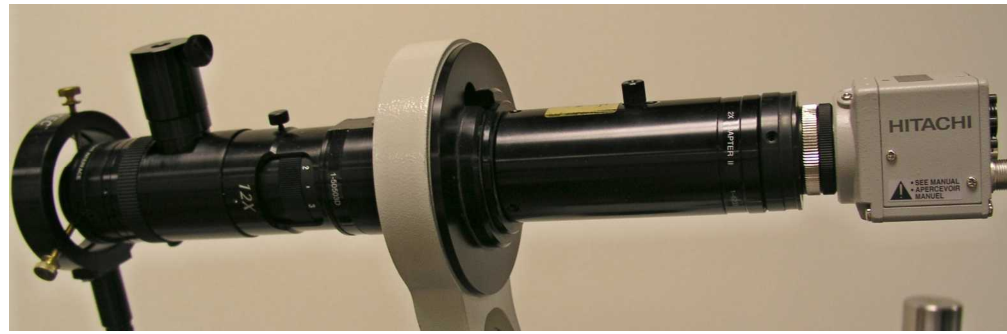
Test Scenarios:

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

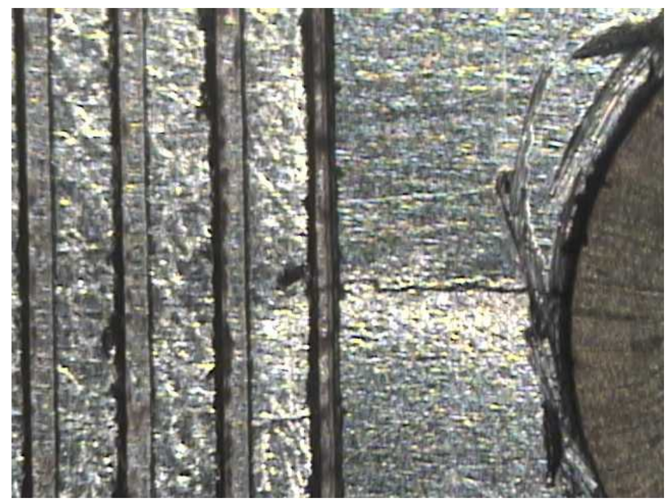


Test Panel Design and Optical Crack Monitoring





Microscope (12X Zoom) interfaced with CCD camera and digital image analysis

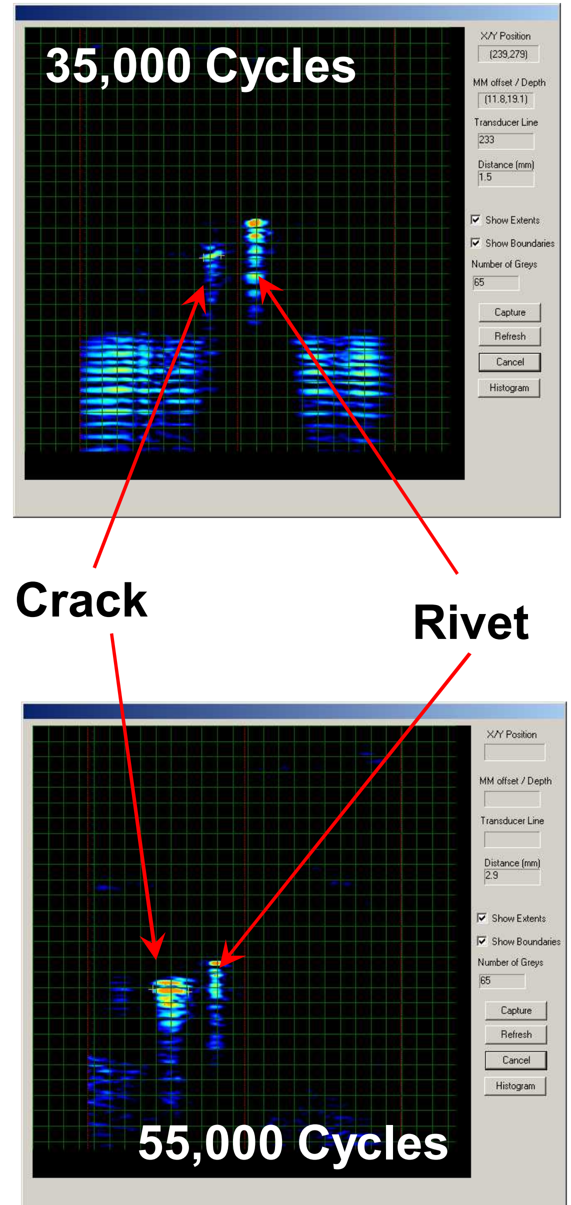


Crack Emanating from Rivet Site

Crack length measured by digital comparison with known length

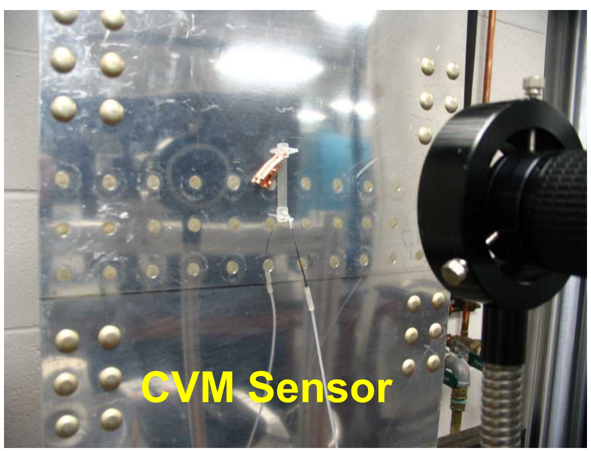
Supplemental NDI Crack Monitoring

USUT Ultrasonic System



Test Procedure – Lab Monitoring with SIM-8 Followed by Check with Field PM-4 Device

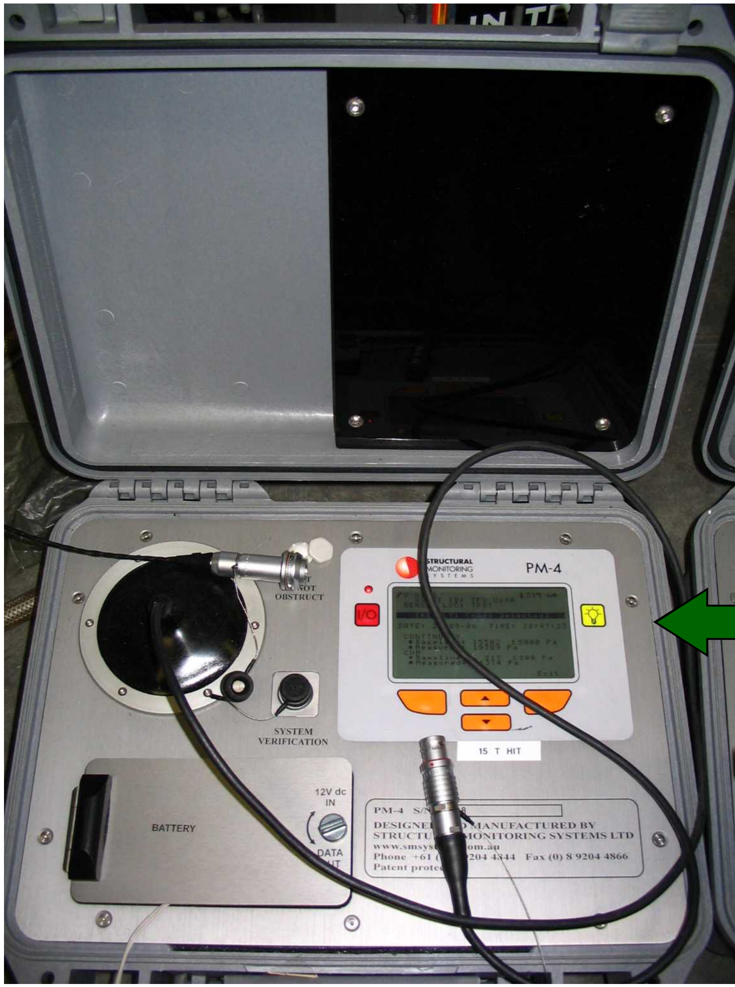
- **Panels loaded into fixtures**
- **Baseline images of fasteners taken with optical microscope camera and USUT ultrasound**
- **Sample fatigued at R-ratio of 0.1 at 17 ksi until crack visually detected by CCD camera**
- **Sensor monitored to check for crack detection**
- **Crack growth closely measured while CVM sensors are periodically monitored to determine <u>permanent</u> alarm threshold**

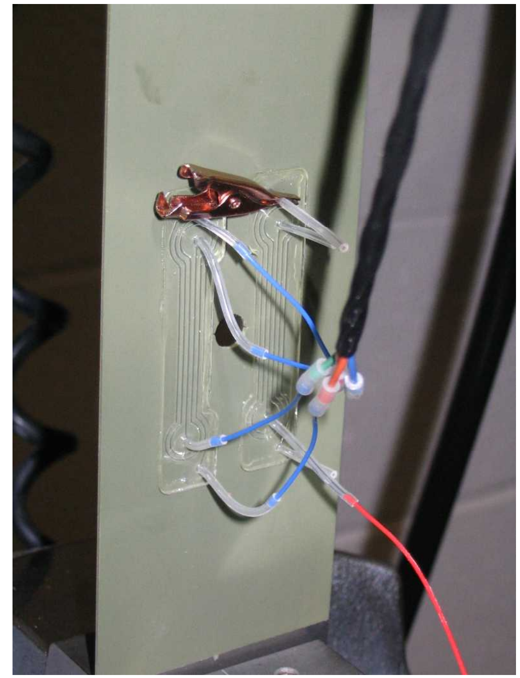

CVM Sensor

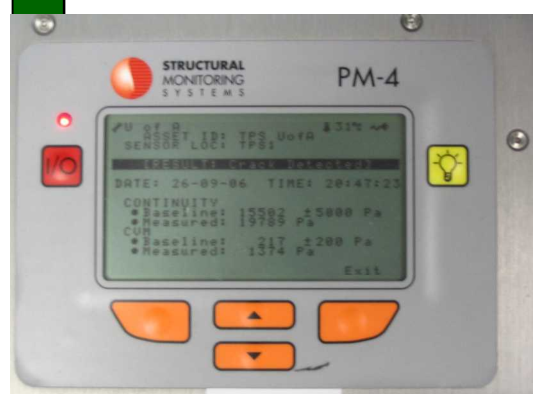
Differential Monitor (SIM-8)

Vacuum Source (KVAC-4)

Monitoring CVM Sensors in the Field with a PM-4 Device







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:

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

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

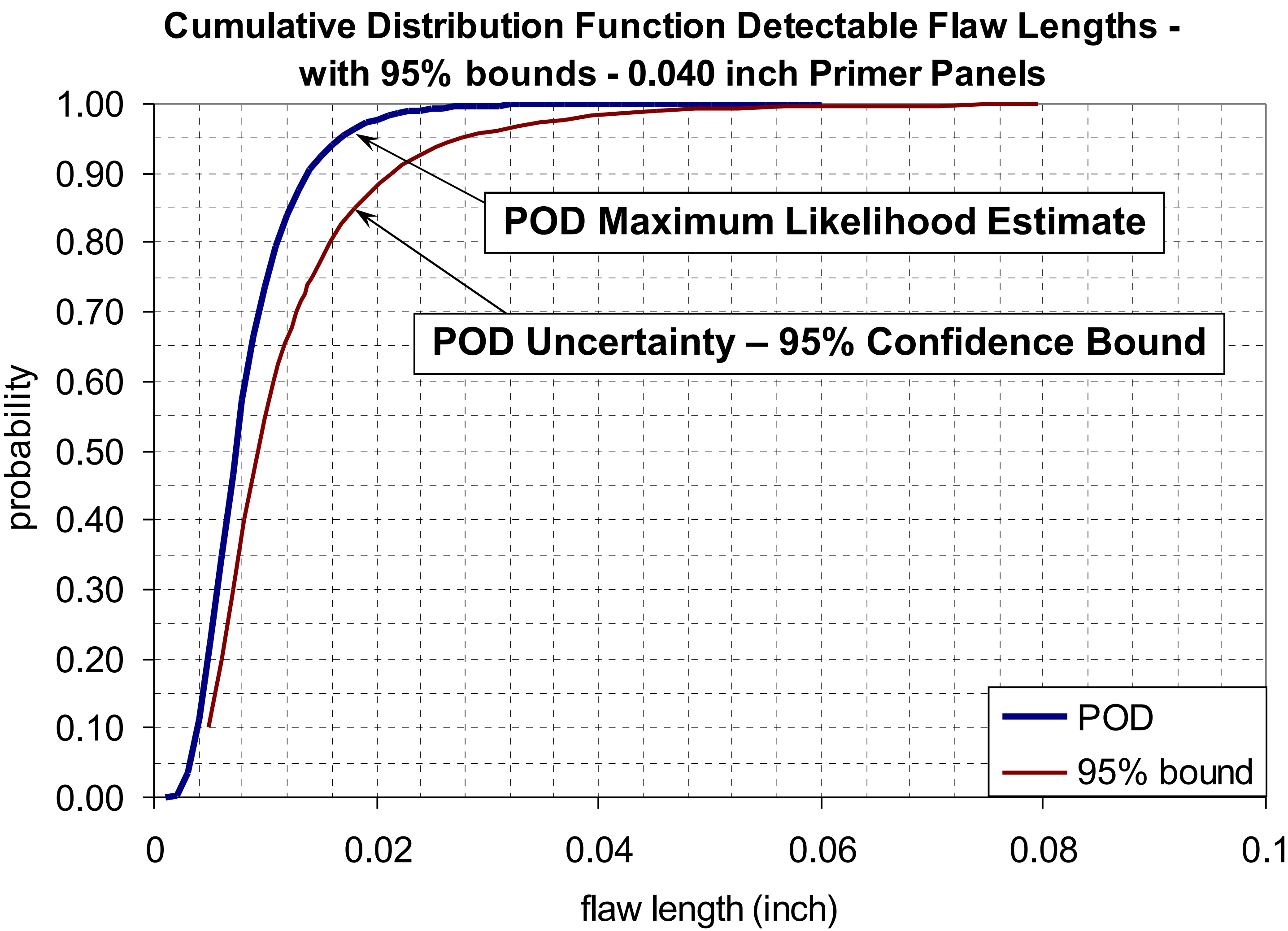
Description: 0.040 inch thick panel (primer surface)

PHASE 2 TESTS						
Panel	**Fastener Crack Site**	**Distance from Fastener (inches)**	**Crack Length at CVM Detection (growth after install in inches)**	**SIM-8 Reading ΔPa (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

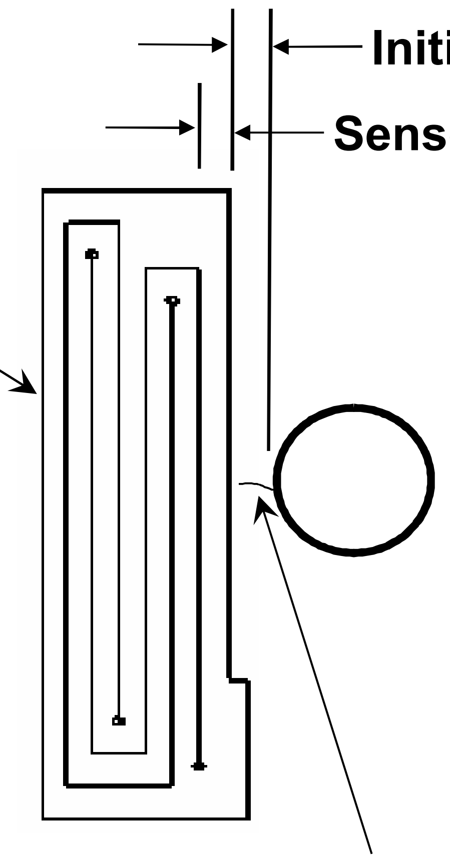
90% POD Level	False Calls
0.021"	0

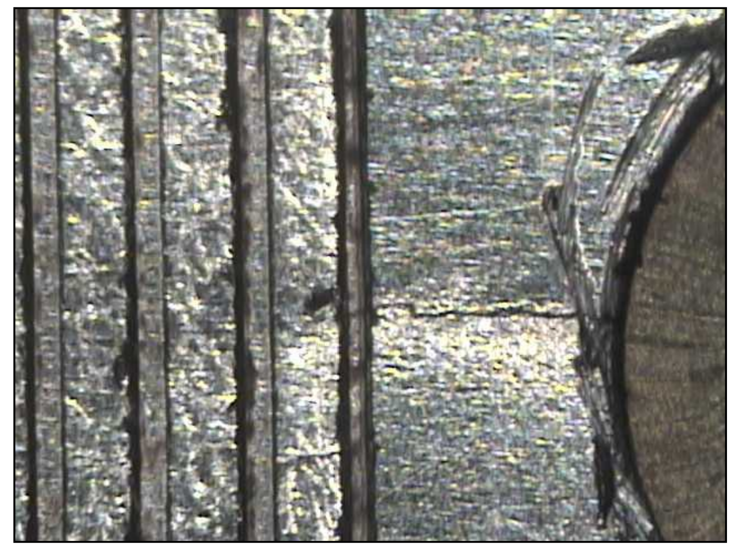
[all panels are 2024-T3 alum. (AMS-4040, 41, QQ-A-250/5) with 0.0005" th. clad]

Sample Probability of Detection Curves for CVM



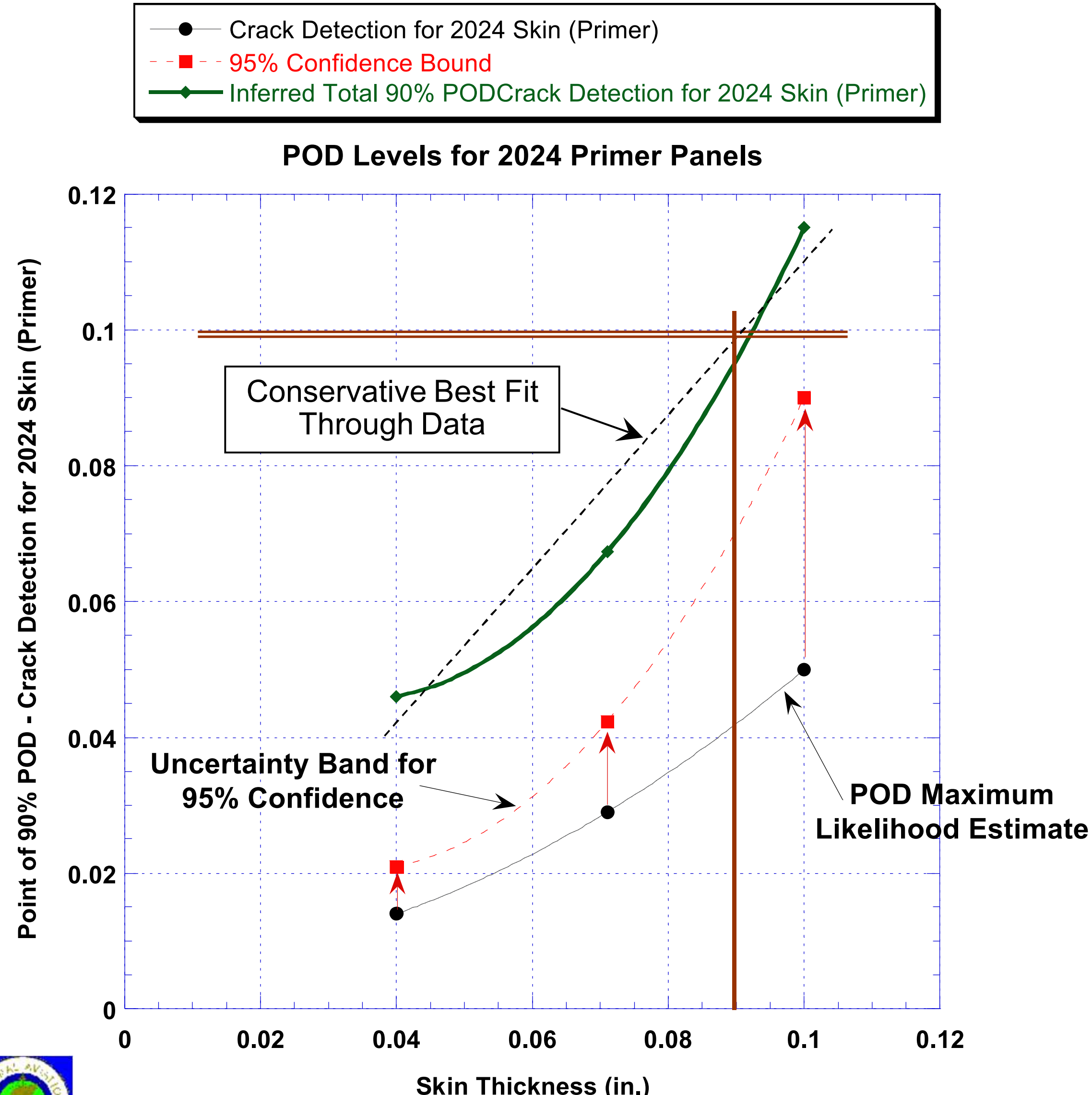
Determining Final CVM Crack Detection Level from Crack "Lag" Values





Total Crack Length at Detection = CVM Lag Detection + 0.014" + 0.010"

Overall Probability of Detection Values as a Function of Material Thickness



Field Evaluation of Sensor Applications

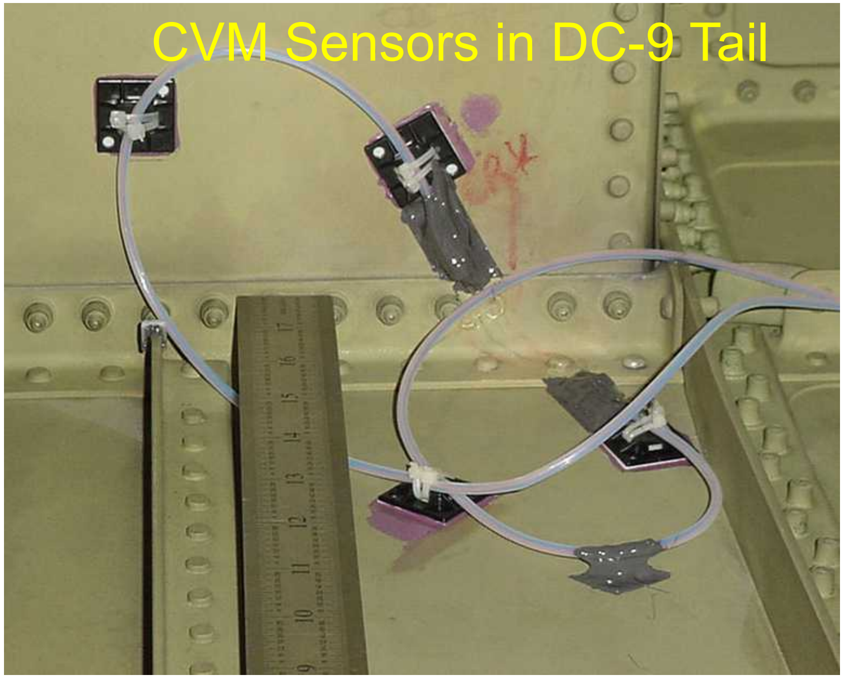
To assess the long-term viability of CVM sensors in an actual operating environment, sensors have been installed on the following civil aircraft for functional evaluation:

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

Field Evaluation of Sensor Applications

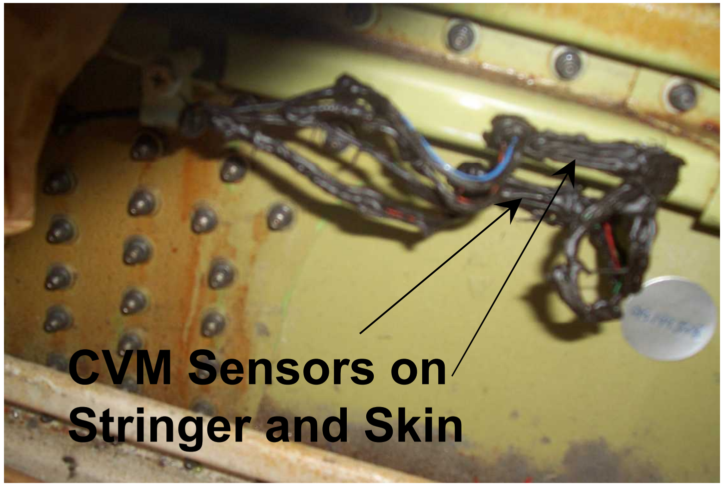
Environmental Durability Testing

- Project specifies 2 year sensor flight trials required
- First sensors were MFA/TRI fuel tank sensors installed in DC-9 empennage in Feb 2004
- Installations conducted at NWA and Delta in April 2005
- 22 sensors installed and connected on 4 aircraft
- Delta and NWA indicate good data from connected sensors on AC thus far



DC-9 Lower Wing Spar

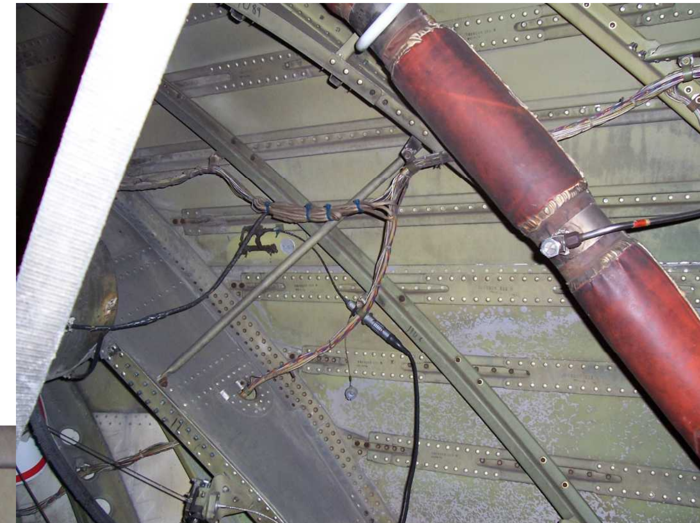
NWA Aft Baggage Compartment Sensor (A/C 9968)

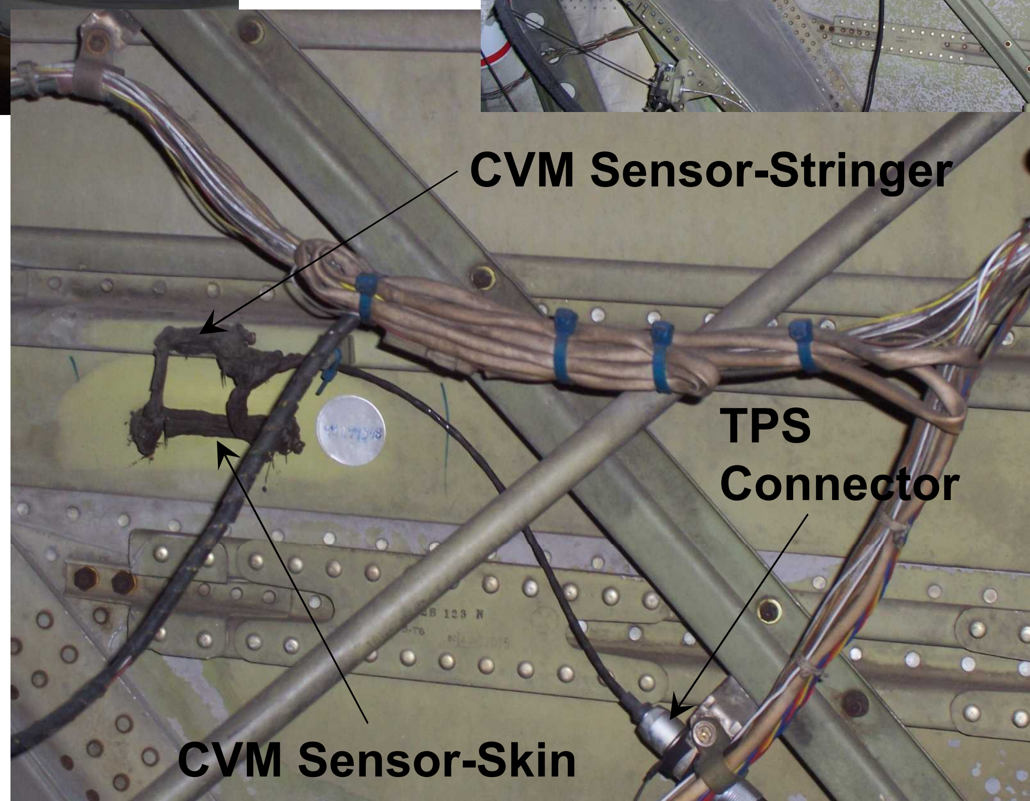


TPS connector routed to access panel

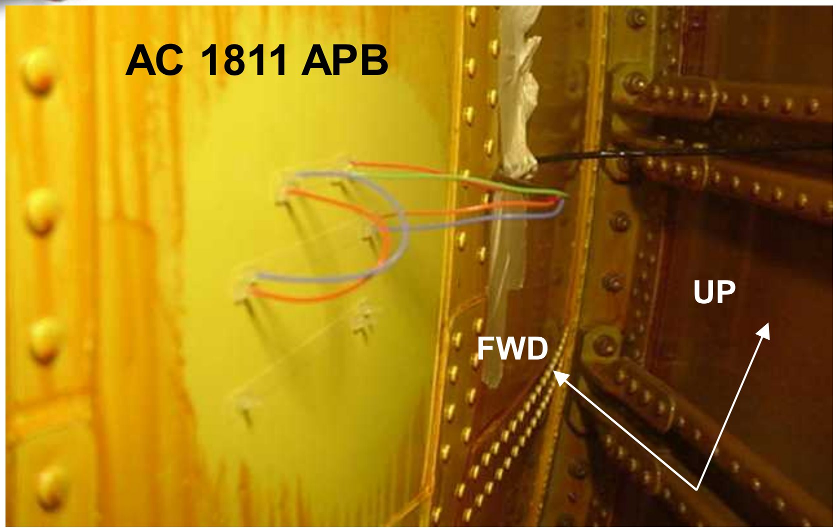
Monitoring CVM with PM-4 device

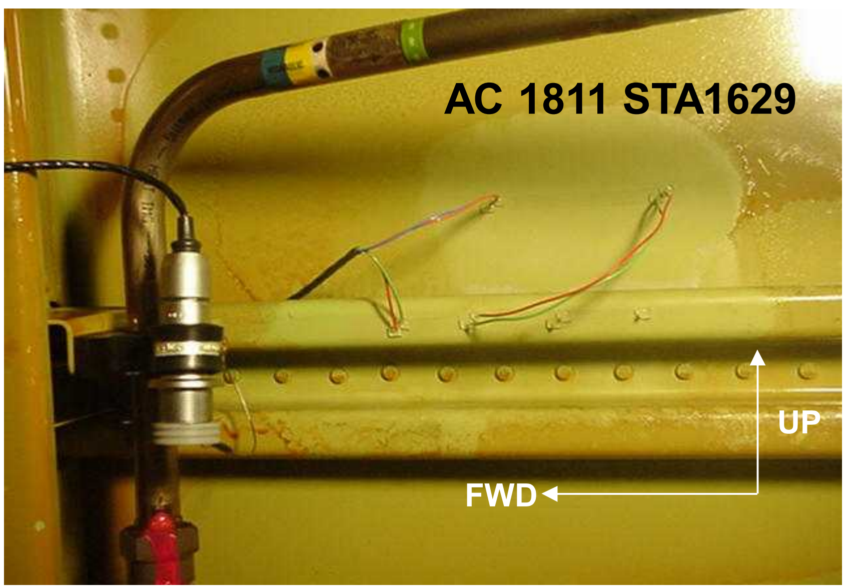
NWA Empennage Sensor (A/C 9968)

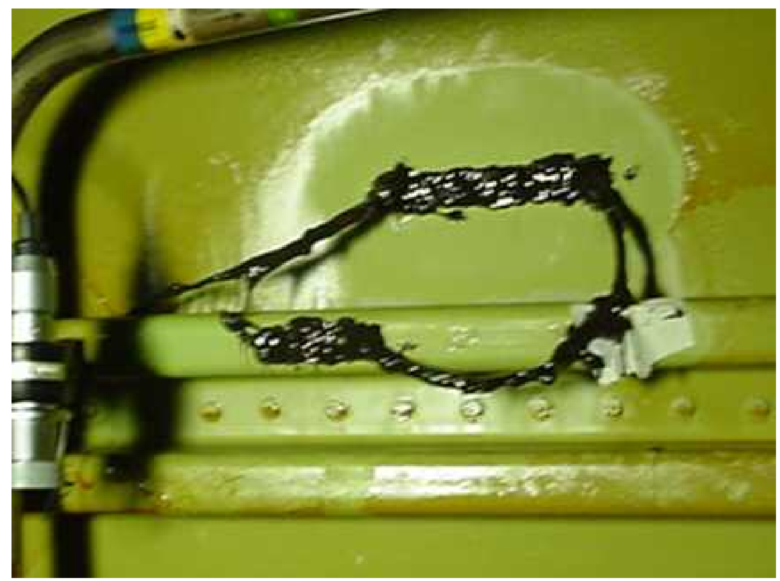




Delta Air Lines Field Installations







Validation of CVM Sensors for Modification of NDT Standard Practices Manual

- **CVM sensor detects cracks in the component it is adhered to**
- **System is non-electric (vacuum based)**
- **Inspection process and diagnosis is fully automated**
- **CVM system is fail-safe (inert sensors produce an alarm)**
- **Materials used in sensor and adhesive are approved for aircraft**
- **Remaining tasks**
  - ➢ **Wrap up monitoring and overall assessment of CVM sensors flying on aircraft**
  - ➢ **Address peripheral issues such as effects of Corrosion Inhibiting Compounds on CVM function (proper sealant of sensors to prevent blockage)**

Application of CVM Sensors for Aircraft Crack Detection

- Integration of CVM in NDT Standard Practices Manuals (foundation)
- AMOC for SBs and ADs – safety driven use is achieved in concert with DERs
- Application-oriented testing to “bridge” general CVM performance data (integrate with ongoing fatigue tests)
- Focused testing to evaluate custom sensor designs
- NDI Reference Standards needed – CVM on fatigue crack coupon
- Training – ensure proper installation and monitoring
- Ensure sensitivity requirements are met

Application and Certification of Comparative Vacuum Monitoring Sensors for In-Situ Crack Detection

Dennis Roach 1, Jeff Kollgaard 2, Steve Emery 3, Jeff Register 4, Kyle Colavito 5, Dave Galella 6
1 FAA Airworthiness Assurance Center at Sandia National Laboratories, 2 Boeing Commercial Aircraft, 3 Structural Monitoring Systems, 4 Aerotechnics, 5 University of Arizona, 6 FAA

ABSTRACT

Current aircraft maintenance operations require personnel entry into normally-inaccessible or hazardous areas to perform mandated, nondestructive inspections. To gain access for these inspections, structure must be removed, sealant must be removed and restored, fuel cells must be vented to a safe condition, or other disassembly processes must be completed. These processes are not only time consuming but they provide the opportunity to induce damage to the structure. The use of in-situ sensors, coupled with remote interrogation, can be employed to overcome a myriad of inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage. Furthermore, prevention of unexpected flaw growth and structural failure could be improved if on-board health monitoring systems are used to more regularly assess structural integrity. The Airworthiness Assurance NDI Validation Center (AANC) at Sandia Labs, in conjunction with Boeing, the University of Arizona, Structural Monitoring Systems, and interested airlines is currently conducting a research program to develop and validate Comparative Vacuum Monitoring (CVM) Sensors for crack detection. CVM sensors are permanently installed to monitor critical regions of a structure. The CVM sensor is based on the principle that a steady state vacuum, maintained within a small volume, is sensitive to any leakage. Vacuum monitoring is applied to small galleries that are placed adjacent to a second set of galleries maintained at atmospheric pressure. If a flaw is not present, the low vacuum remains stable at the base value. If a flaw develops, air will flow from the atmospheric galleries through the flaw to the vacuum galleries. A crack in the material beneath the sensor will allow leakage resulting in detection via a rise in the monitored pressure. The initial goal of this project is to provide Boeing Commercial Aircraft with sufficient data to place CVM sensor technology into the Nondestructive Testing Standard Practices Manual. The test specimens include those designed to simulate the Boeing aircraft lap joint and others with single crack origination sites. The test matrix studied the affects of surface coating, skin thickness, and material type on the performance of the CVM sensors. Statistical methods using one-sided tolerance intervals were employed to derive Probability of Detection (POD) levels for each of the test scenarios. The result is a series of flaw detection curves that can be used to propose CVM sensors for aircraft crack detection. Complimentary, multi-year field tests were also conducted to study the deployment and long-term operation of CVM sensors on aircraft. This paper presents the quantitative crack detection capabilities of the CVM sensor, its performance in actual flight environments, and the prospects for structural health monitoring applications on commercial aircraft.