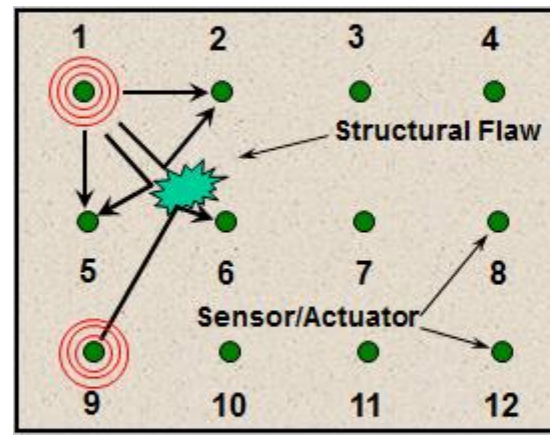
Comparison of Multiple Statistical Methods for Calculating the Probability of Detection from SHM Systems

SAND2017-9630C



Dennis Roach
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FAA WJH Tech Center

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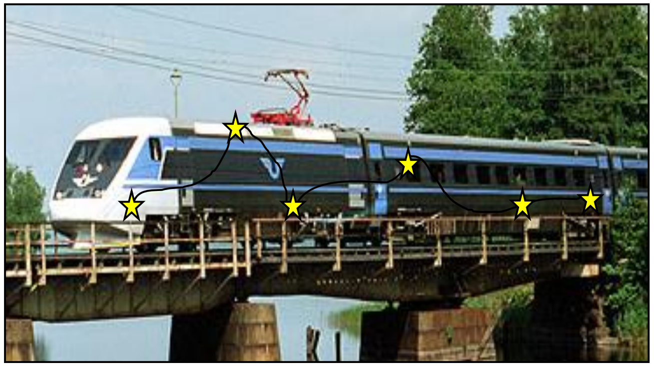
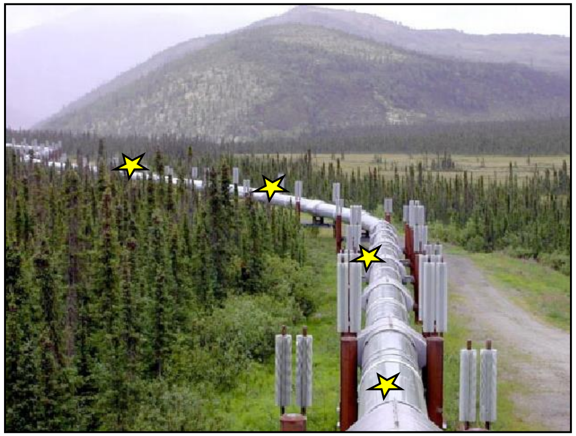
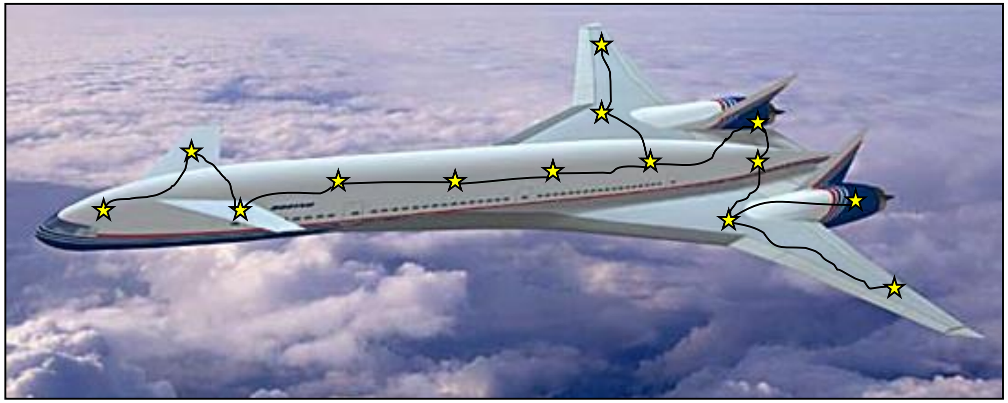
Distributed Sensor Networks for Structural Health Monitoring

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

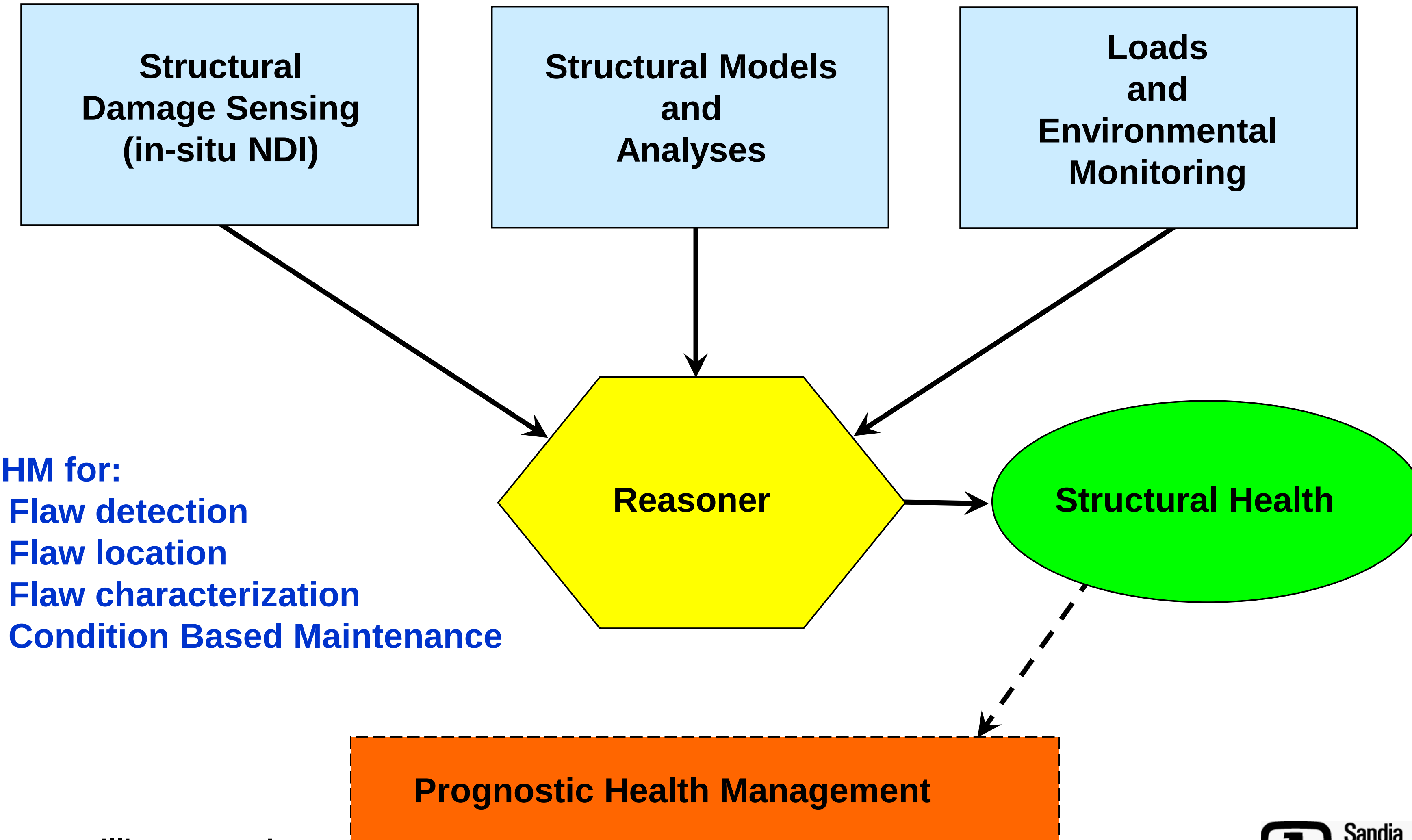






Structural Health Monitoring

- Courtesy of Eric Lindgren, AFRL



SHM for:

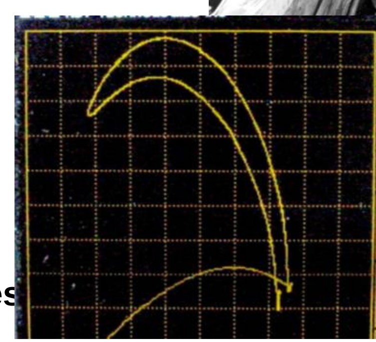
- Flaw detection
- Flaw location
- Flaw characterization
- Condition Based Maintenance

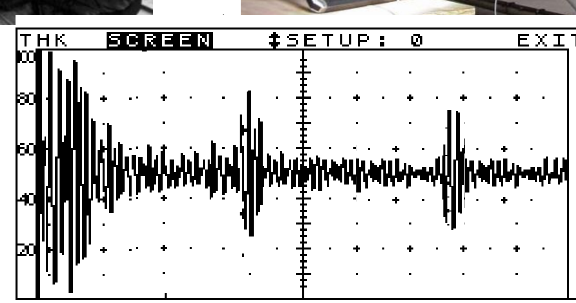
The Trouble with Math or…..
How do we calculate DT ??

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

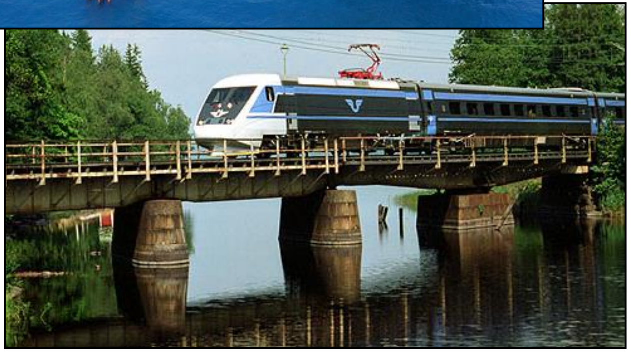
Difficult Conditions

Lots of Rapid Data Interpretation





Wide Range of SHM Uses

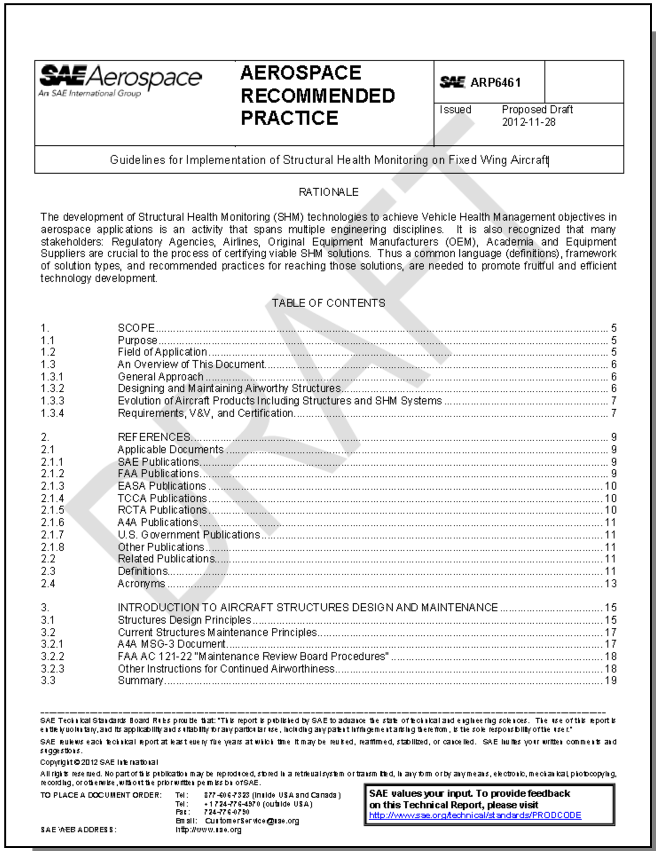


Aerospace Industry Steering Committee on Structural Health Monitoring (AISC SHM)

- **Mission: 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 development of cross-industry guidebooks describing approaches to safely deploy SHM.**

"Guidelines on the Implementation of Structural Health Monitoring on Fixed Wing Aircraft"



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.

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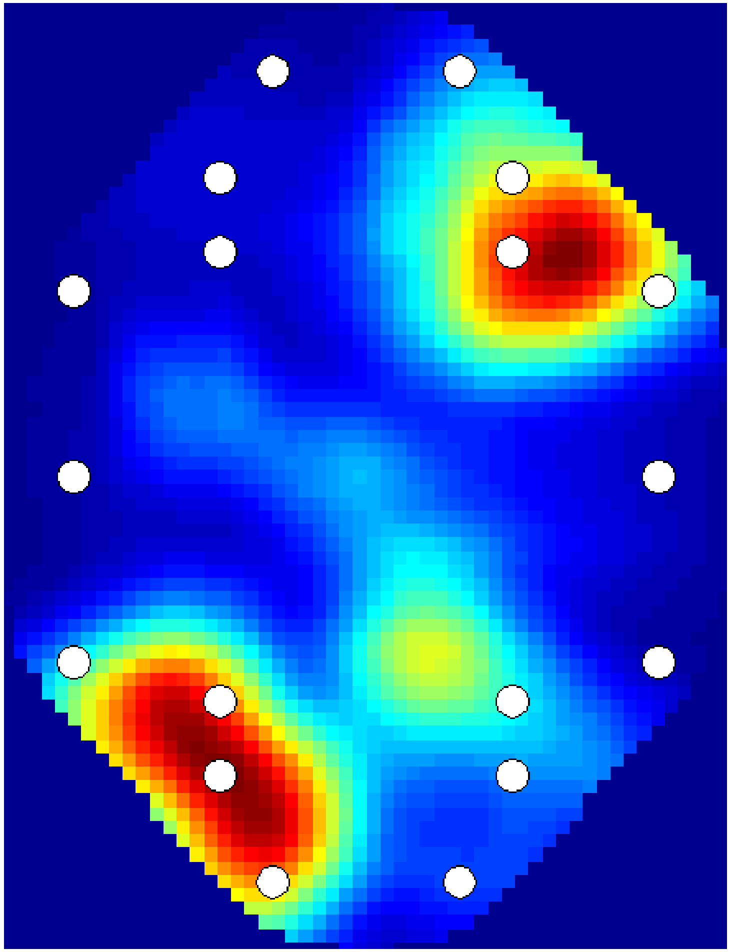
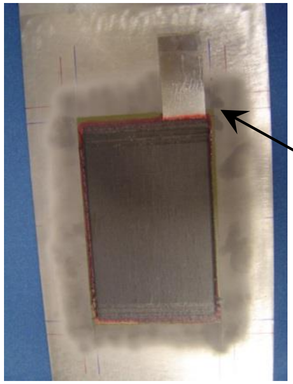
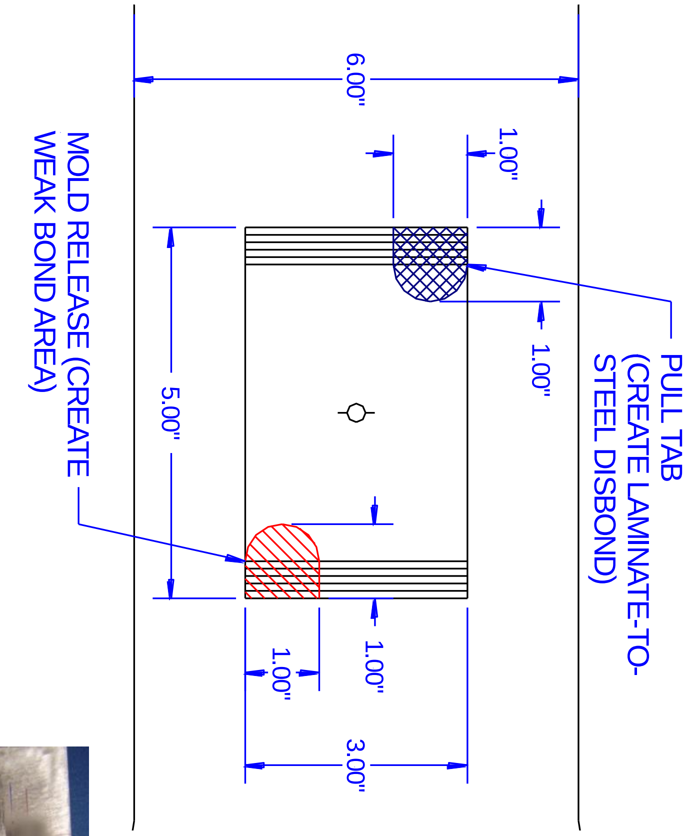
20th meeting of AISC-SHM at OGMA MRO
Lisbon, Portugal
April 2016

Disbond Detection & Growth Monitoring with Piezoelectric Sensors



After mold release flaw growth (50 KHz inspection)



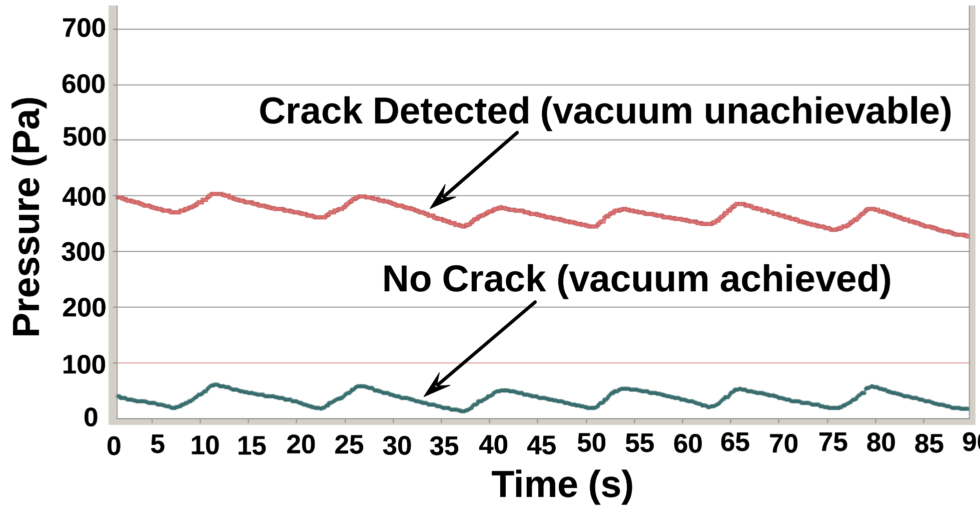


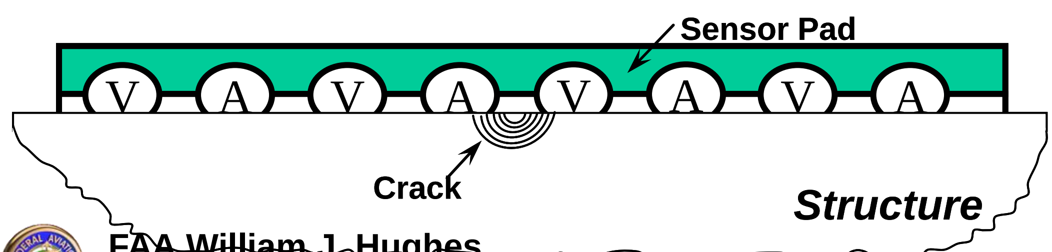
Pull tab flaw

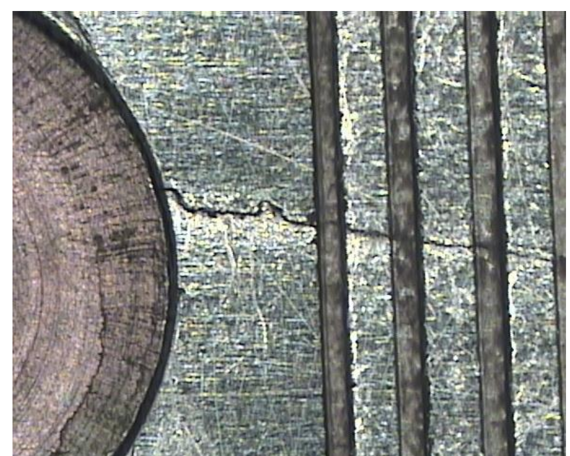
Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries
- 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

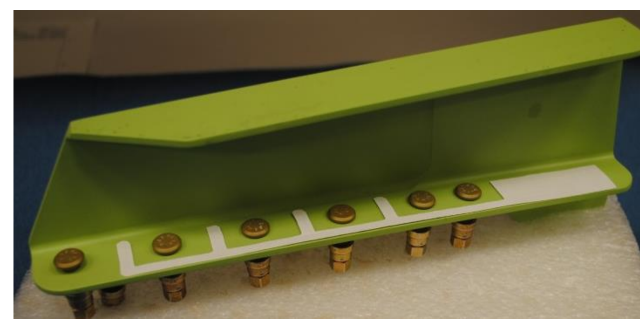






CVM Sensor Network Applied to 737 Wing Box Fittings

Alternate Means of Compliance with Current Visual Inspection Practice



Validation of Structural Health Monitoring Solutions for HUMS

Expected Outcome

- Demonstration of a viable SHM system utilizing proven sensors to detect representative rotorcraft structural damage
- A model for the inclusion of structural health data into HUMS-based decision making processes
- Integrate results into rotorcraft AC 29-2C, MG15 to ensure safe adoption of SHM solutions
- Documented efforts to move the proposed system through the certification process possibly including:
  - Alternate Means of Compliance (AMOC)
  - Mods to SBs/ADs; STCs
  - Investigating potential accrual of maintenance credits
- The Rotorcraft subcommittee of the SAE AISC-SHM committee plans to develop industry guidance for SHM use Rotorcraft.
- Their focus is to tie the SHM sensors and data collected into the HUMS system. This is a new use for HUMS and the research being performed will support this guidance.

Sikorsky

Comparative Vacuum Monitoring System - Local SHM of Cracks Emanating from Fastener and Nutplate Holes

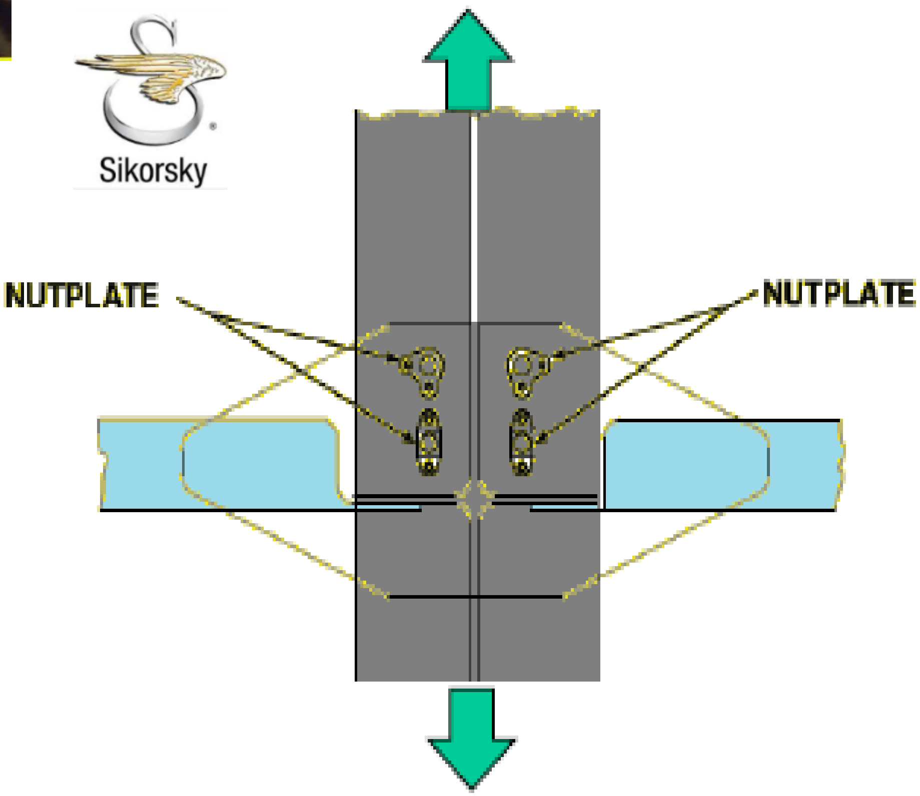
Inner Cap

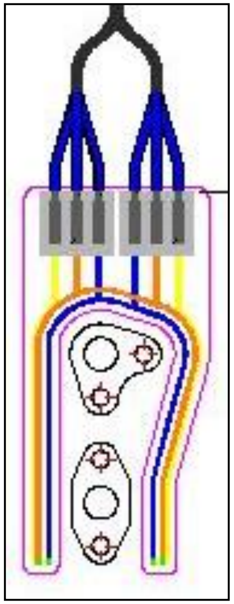
S-92 Frame Gusset

- Failure History - cracking begins at nutplate holes on inner cap; grows outward to edge of frame
- Consistent crack behavior

- Thickness/materials are common for frame/beam caps – good extrapolation to other high-interest locations for rotorcraft SHM

Sikorsky

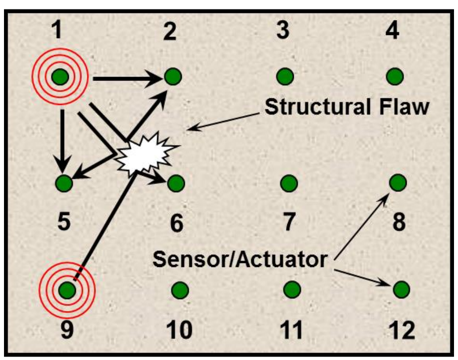


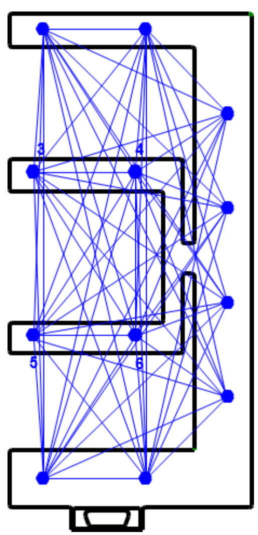


CVM Sensor Design

Quantifying Flaw Detection Performance of SHM Systems

- Detection Mode - fixed sensor with damage growth into sensor (network) monitoring regions
- Factors Effecting SHM System Response - must control/recognize these variables during flaw detection testing
  - Flaw size, shape, and orientation
  - Flaw location relative to the sensors,
  - Operational and environmental effects
  - Presence of multiple flaws within a sensor network
  - Residual strains
  - Fretting of joints
- SHM System Reliability – also includes SHM sensor repeatability (manuf. QA), system durability (environmental deterioration?)

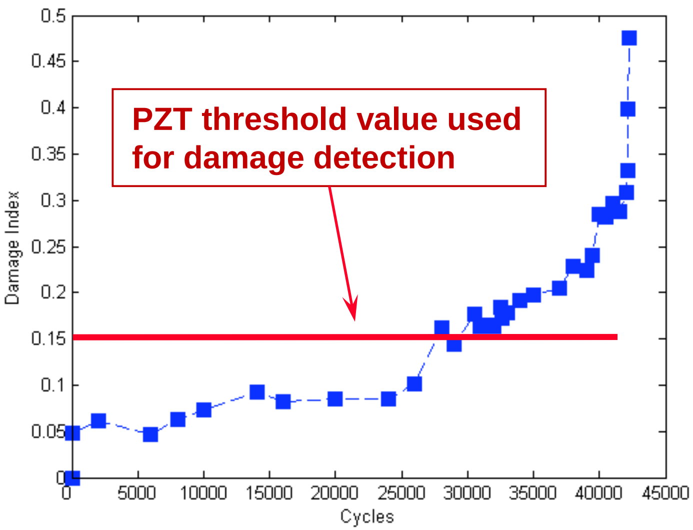


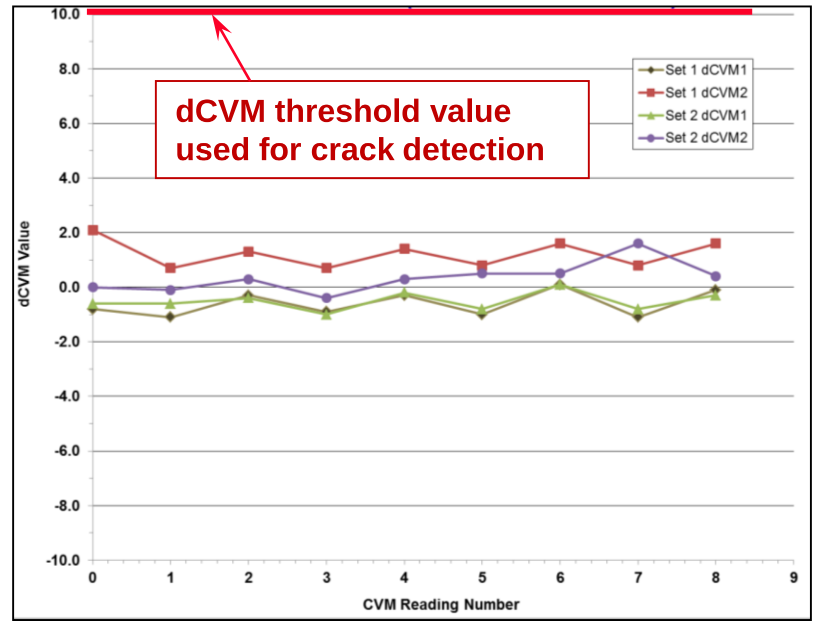


PZT Sensor Network "Coverage"

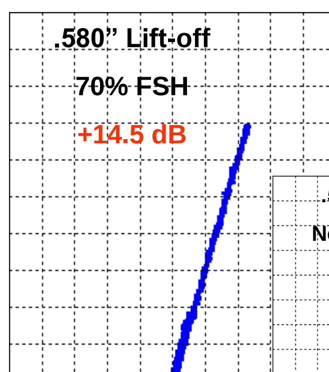
SHM Information – Establishing Detection Thresholds to Minimize Interpretation or Data Analysis

- **Automated data analysis is the objective – produce a "Green Light – Red Light" approach to damage detection**
- **Final assessment and interpretation by trained NDI personnel**
- **Ability to assign clear thresholds will effect methods to establish POD**

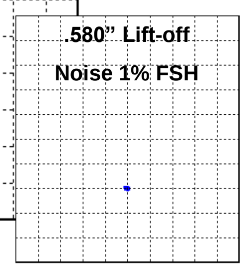




A



B



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

POD Assessment Using One-Sided Tolerance Interval

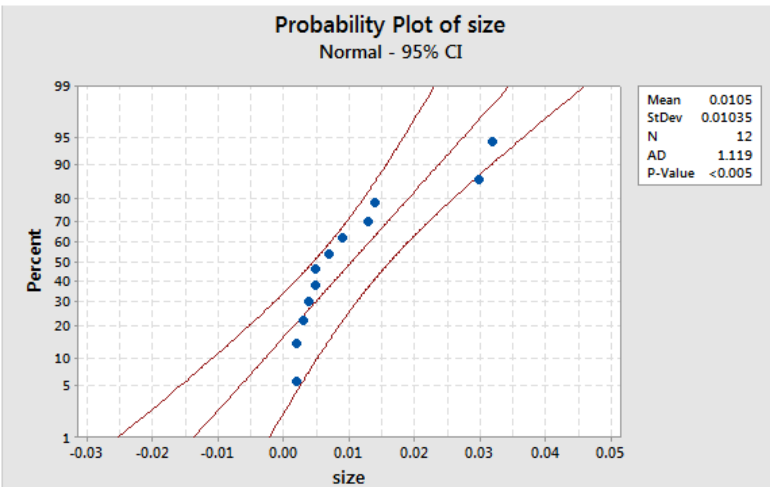
- **Interval to cover a specified proportion of a population distributed with a given confidence – related to measures of process capability**
- **One-sided Tolerance Interval – estimates the upper bound which should contain a certain percentage of all measurements in the population with a specified 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:**

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

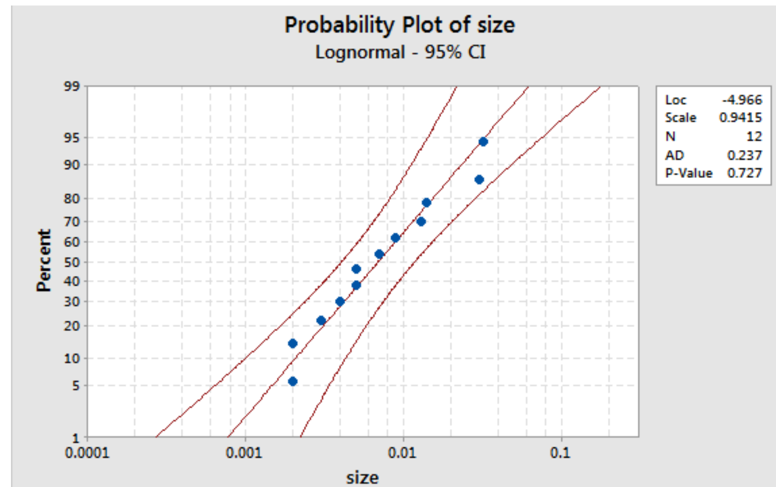
- **Interested in a 1-tailed interval (utilize "+" in equation); upper limit of TI. Uncertainty in knowing the true mean and population variance requires that the estimate of the range of values encompassing a given percentage of the population must increase to compensate.**

POD Assessment Using One-Sided Tolerance Interval

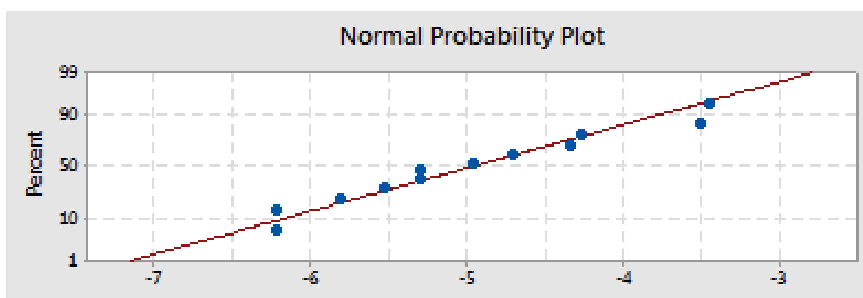
- Assume that the distribution of flaws is such that the logarithm of the lengths (strictly positive sizes) has a Gaussian distribution (log-normal distribution)
- Validity depends on distribution on the flaw lengths at which detection is first made – lognormal distribution plots on straight line with data clustered near 50th percentile
- Anderson-Darling test requires P-value > 0.05



Normal Distribution



Lognormal Distribution



Normal plot of log values of data

$\bar{X}$

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:**

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

X = Mean of detection lengths

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

S = Standard deviation of detection lengths

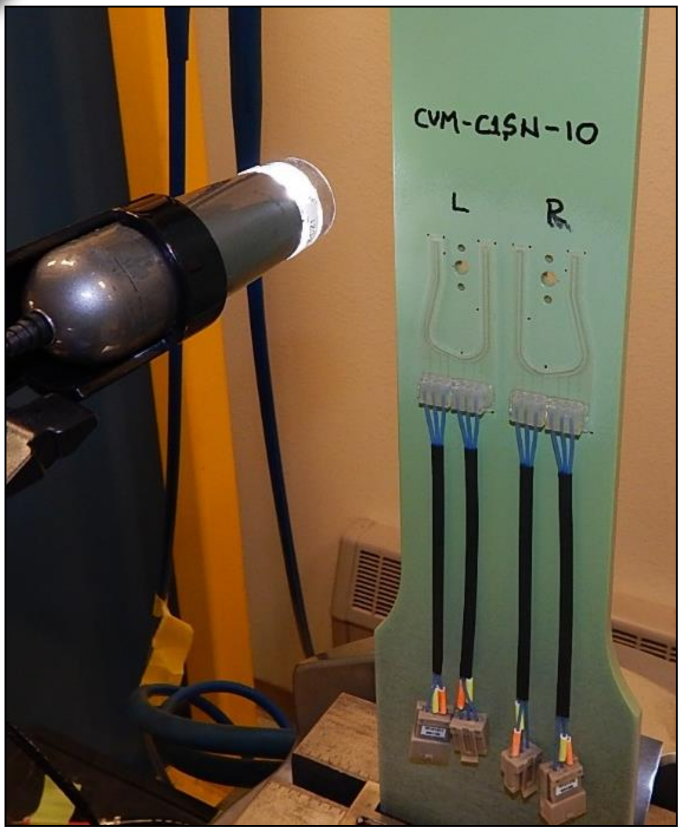
n = Sample size

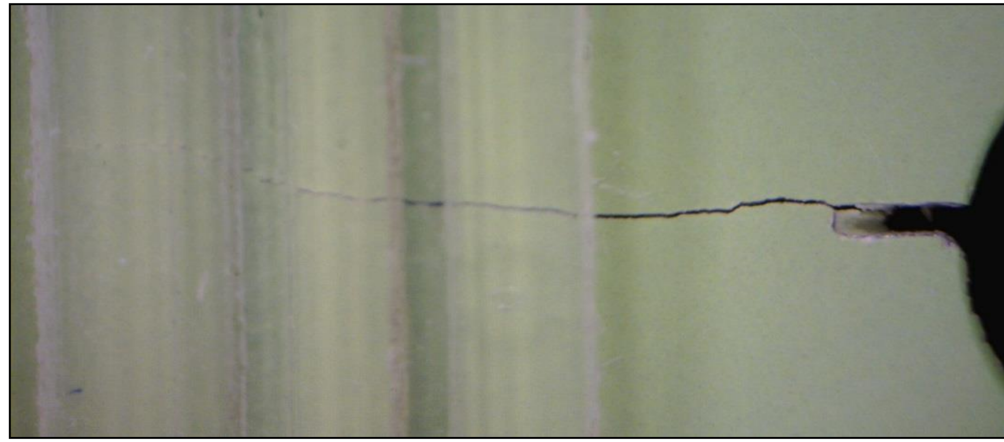
α = Detection level

ɣ = Confidence level

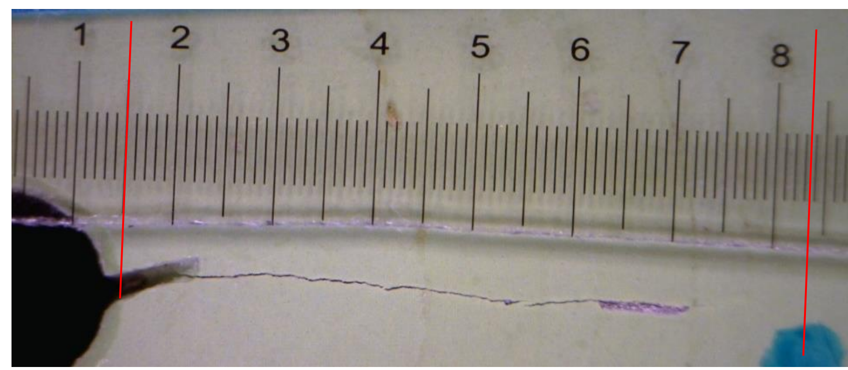
CVM Performance Testing – Mickey Mouse Nut Plate

Microscope Camera Records Crack Growth





Cracks viewed under load to track growth and show engagement with CVM galleries



Sample Data Recorded for Each Test Specimen

Crack Length = 6.85 mm = 0.270 in
1dCVM = Gallery 1 = 4.2
2dCVM = Gallery 2 = 1.1
SIM2 = 16,250 Pa
Cycles = 20,278

CVM Performance Testing Results – Mickey Mouse Nut Plate

Sikorsky Config-2 Mickey Mouse Nutplate CVM Performance Tests								
Specimen No.	CVM Sensor ID	Fatique Cycles at permanent CVM Crack Detection	Sensor Distance from Hole (in)	Crack Length Under Sensor at CVM Detection a (in)	Total Crack Length (in)	Dynamic SIM-8 Reading Gallery 1 (Pa)	PM200 Reading (1dCVM)	PM200 Reading (2dCVM)
CVM-C2MMN-1	Left	17,404	0.130	0.138	0.268	15330	4.2	1.4
CVM-C2MMN-1	Right	17,906	0.106	0.111	0.217	13424	4.5	1.7
CVM-C2MMN-2	Left	23,099	0.119	0.180	0.299	17100	4.2	3.1
CVM-C2MMN-2	Right	20,514	0.123	0.125	0.248	17100	4.1	0.2
CVM-C2MMN-3	Left	20,128	0.113	0.135	0.248	14600	4.2	1.2
CVM-C2MMN-3	Right	26,483	0.140	0.242	0.382	18350	5.2	3.7
CVM-C2MMN-4	Left	22,888	0.096	0.278	0.374	18600	7.3	6.4
CVM-C2MMN-4	Right	Specimen Broke - No Data						
CVM-C2MMN-5	Left	23,078	0.101	0.220	0.321	17650	4.1	1.7
CVM-C2MMN-5	Right	20,278	0.124	0.146	0.270	16250	4.2	1.1
CVM-C2MMN-6	Left	14,962	0.097	0.129	0.226	11300	4.4	0.5
CVM-C2MMN-6	Right	14,485	0.106	0.181	0.287	16800	4.2	3
CVM-C2MMN-7	Left	19,979	0.100	0.221	0.321	17600	2.9	6.5
CVM-C2MMN-7	Right	18,827	0.110	0.169	0.279	15000	4.3	0.1
CVM-C2MMN-8	Left	13,057	0.112	0.168	0.280	15500	4.2	0
CVM-C2MMN-8	Right	15,725	0.095	0.314	0.409	18280	4.9	3.7
CVM-C2MMN-9	Left	15590	0.127	0.198	0.325	17400	4.1	1.5
CVM-C2MMN-9	Right	15,316	0.114	0.219	0.333	17350	4.5	3.9
CVM-C2MMN-10	Left	12,877	0.134	0.193	0.327	17550	4.5	2.5
CVM-C2MMN-10	Right	11,660	0.081	0.177	0.258	17500	1.6	4.3

Avg CVM Detection	0.187
CVM Detect Std Dev	0.053
Avg Dist From CVM Edge to Hole Edge	0.112

CVM Performance Testing Results – MM Plate
OSTI Probability of Detection Calculation

CVM Crack Detection Data

Distance from Hole to Sensor Edge	Total Crack Length a (in)	Crack Length Under Sensor at CVM Detection a (in)	Log of Crack Length at CVM Detection a (In)
0.13	0.268	0.138	-0.860120914
0.106	0.217	0.111	-0.954677021
0.119	0.299	0.180	-0.744727495
0.123	0.248	0.125	-0.903089987
0.113	0.248	0.135	-0.869666232
0.14	0.382	0.242	-0.616184634
0.096	0.374	0.278	-0.555955204
0.101	0.321	0.220	-0.657577319
0.124	0.270	0.146	-0.835647144
0.097	0.226	0.129	-0.88941029
0.106	0.287	0.181	-0.742321425
0.100	0.321	0.221	-0.655607726
0.110	0.279	0.169	-0.772113295
0.112	0.280	0.168	-0.774690718
0.095	0.409	0.314	-0.503070352
0.127	0.325	0.198	-0.70333481
0.114	0.333	0.219	-0.659555885
0.134	0.327	0.193	-0.714442691
0.081	0.258	0.177	-0.752026734

Average Crack Length at CVM Detection =	0.187
Standard Deviation of CVM Detection =	0.053
Average Dist From CVM Edge to Hole Edge =	0.112

Statistic Estimates on Log Scale

Statistic	Value (in.)	Value in Linear Scale
Mean (X)	-0.745	0.187
Stnd Deviation (S)	0.121325291	0.05348766

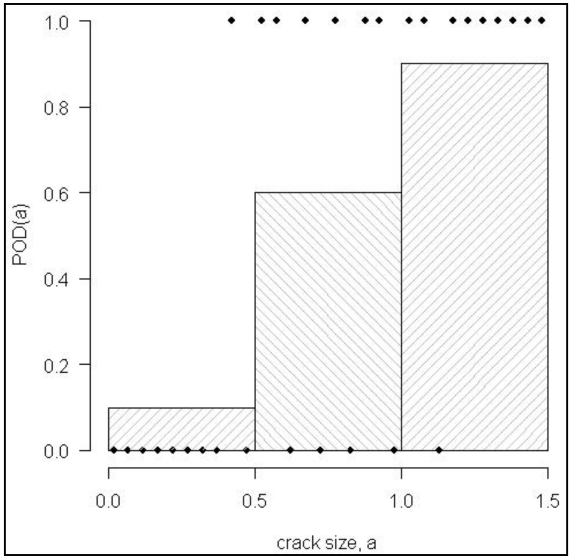
POD Detection Levels
(ɣ = 95%, n = 19)

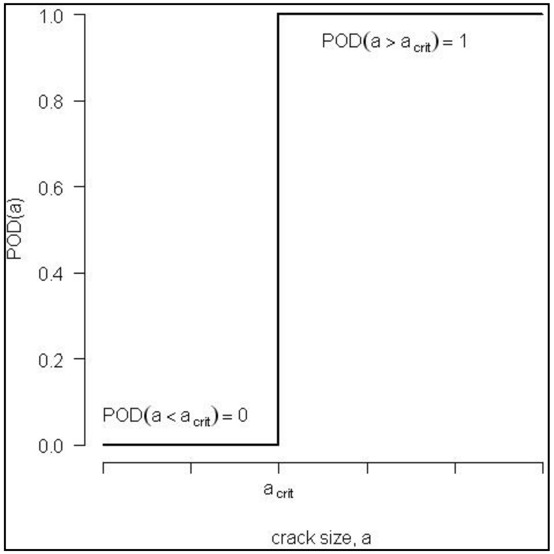
Flaw Size: POD = X + K(S) =	0.310

Overall POD (with sensor offset) = 0.422”

POD Analysis Using Standard Hit-Miss Methodology (Mil-HDBK-1823)

- Early attempts to quantify probability of detection, POD, considered the number, n, of cracks detected, divided by the total number, N, of cracks inspected, to be a reasonable assessment of system inspection capability, POD = n/N. This resulted in a single number for the entire range of crack sizes. Grouping specimens this way improved the resolution in crack size, but the resolution in POD suffers because there were fewer specimens in each range & many factors influence the probability of detecting any one given flaw
- If the SHM system can produce output (detection) that can be reduced to a binary response, a ***hit/miss*** analysis can be used **(*Hit/Miss* POD model)**
- A perfect inspection produces a step function with POD = 1 for $a > a_{crit}$ and POD = 0 when $a < a_{crit}$. It is *not* a POD(a) = constant = 1 because an inspection that finds everything is useless since it cannot discriminate between an actual crack and a benign microstructural artifact, an edge, or a surface blemish.





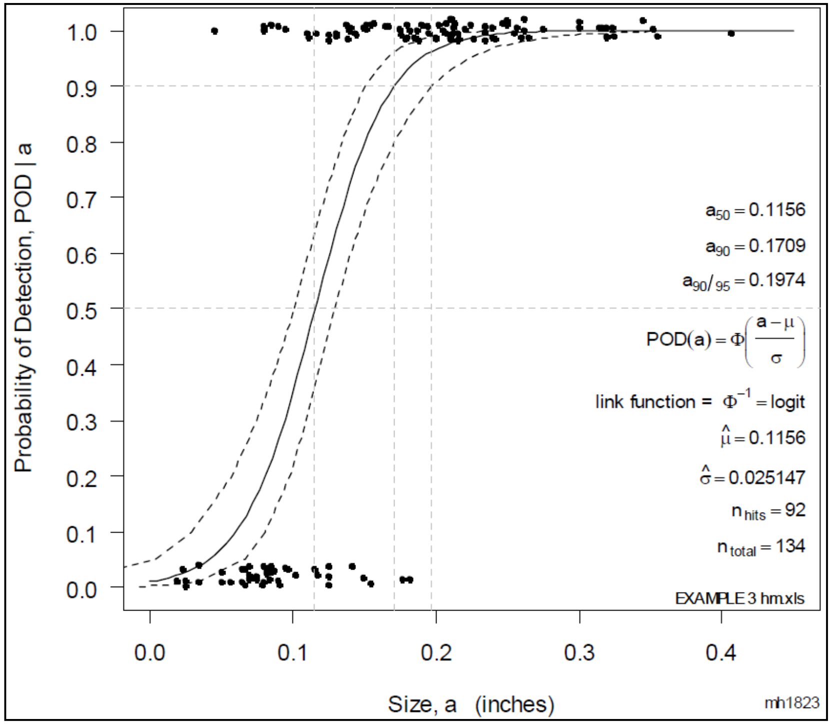
POD Analysis Using Standard Hit-Miss Methodology (Mil-HDBK-1823)

- An efficient use of the binary (***hit/miss***) data is to produce an underlying mathematical relationship between POD and size
- Logistic Regression ***Hit/Miss* POD model** is used to analyze binary (detect/no detect) data

$$\ln[POD(a)/(1 - POD(a))] = \alpha + \beta[\ln(a)]$$

Where "a" is the flaw size and α and β are estimated by maximum likelihood estimates

- Assumption is for no variation in equipment or procedures
- Assumption is all critical factors are controlled in the testing so no need for additional φ·f to describe other factors on the RHS of log regression formula
- Each flaw is either detected or not detected – best estimate for POD(a) is either 0 or 1; use a range of flaws to determine the α and β that maximize the likelihood of the particular sequence of 0's (misses) and 1's (detects) that were observed.



Assumptions in Statistical Data
Can Create Inaccurate Assessments

NDI POD

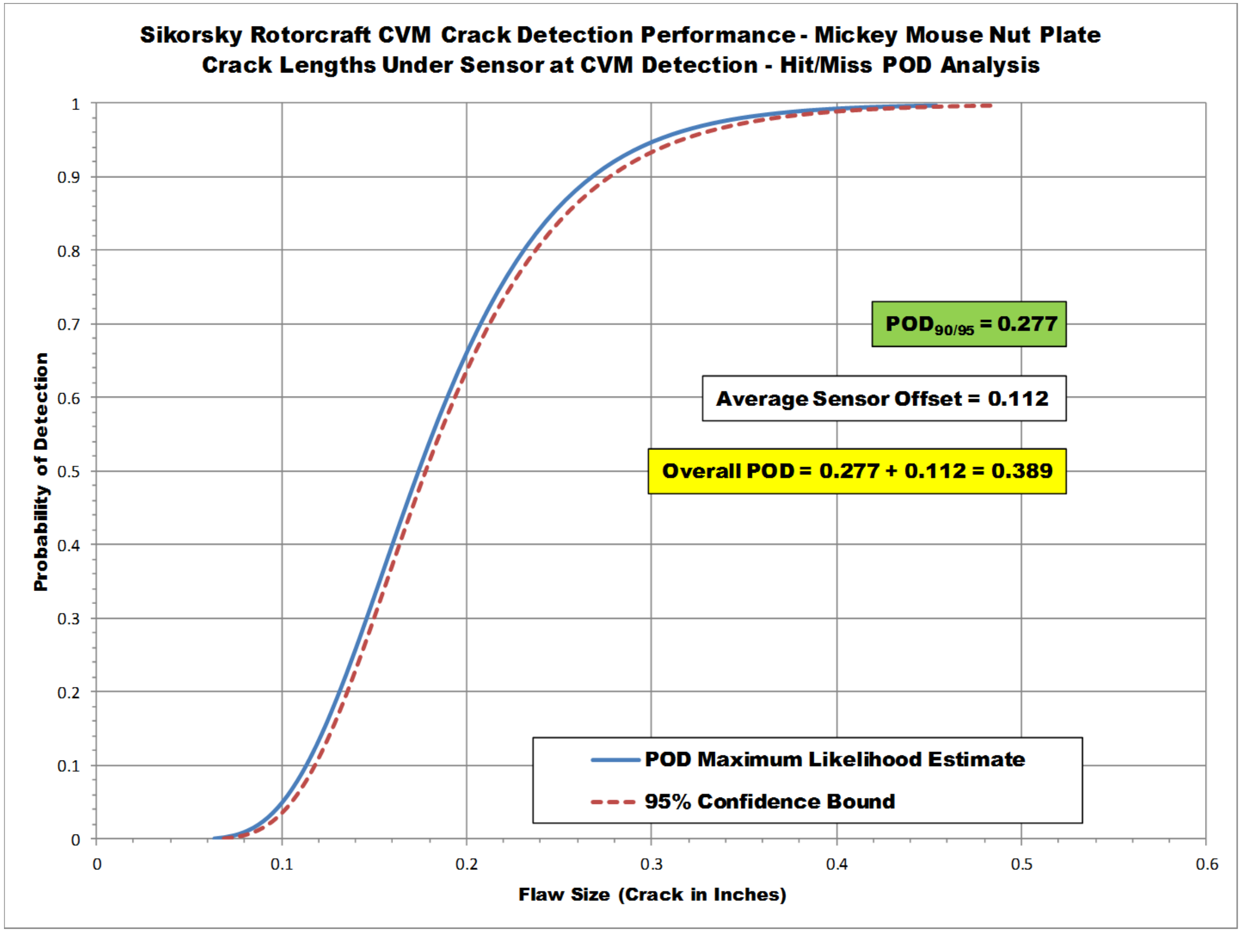
- All Independent Data – independent distribution of seeded cracks; signals at detection are logged (one reading on each target); accounts for operator-to-operator (sensor-to-sensor) variability; accounts for crack-to-crack variability

SHM POD

- Log-Regression (hit-miss) Model - 19 independent tests (cracks); 65 hit-miss data points acquired from 19 tests (not all independent); additional extrapolated data at extremes (small & large cracks) used to populate a complete POD curve
- *â vs a* Model – SHM involves multiple data points from a single, growing crack; multiple *â* responses for each crack
- Took credit for this data as independent data points (Mil-HDBK-1823 calculation). Thus, the confidence interval is reduced. Should it be?
    - ➢ If the sensors, their location, the cracks, and the sensor response is consistent enough that the assumed data is representative, then we are close to the truth
    - ➢ If the actual responses – should many additional tests be conducted – exhibit deviations and lack consistency, then we will have much larger deviation from the truth
- Repeated Measures Data – needed for SHM assessments as all data from a single specimen is repeated data (same sensor, same growing crack)

POD Analysis Using Standard Hit-Miss Methodology – MM Nutplate

Gaussian distribution of hit-miss data was compiled using crack CVM detection length from each test with assumed, missed crack detections below CVM detection level & assumed, hit crack detections above the CVM detection level.



Sikorsky Mickey Mouse Nut Plate Individual CVM Sensor Performance Tests Hit/Miss POD Values			
Specimen No.	CVM Sensor ID	Eddy Current Crack Length at CVM (In)	$POD_{90/95}$
CVM-C2MMN-1	Left	0.138	0.141
CVM-C2MMN-1	Right	0.111	0.114
CVM-C2MMN-2	Left	0.180	0.184
CVM-C2MMN-2	Right	0.125	0.128
CVM-C2MMN-3	Left	0.135	0.138
CVM-C2MMN-3	Right	0.242	0.246
CVM-C2MMN-4	Left	0.278	0.282
CVM-C2MMN-5	Left	0.220	0.224
CVM-C2MMN-5	Right	0.146	0.150
CVM-C2MMN-6	Left	0.129	0.132
CVM-C2MMN-6	Right	0.181	0.185
CVM-C2MMN-7	Left	0.221	0.244
CVM-C2MMN-7	Right	0.169	0.180
CVM-C2MMN-8	Left	0.168	0.174
CVM-C2MMN-8	Right	0.314	0.318
CVM-C2MMN-9	Left	0.198	0.201
CVM-C2MMN-9	Right	0.219	0.222
CVM-C2MMN-10	Left	0.193	0.197
CVM-C2MMN-10	Right	0.177	0.181
Cumulative			0.277

19 Acquired Data Points at Detection (Hits) Plus Extrapolated Hit/Miss Data Points on Either Side

CVM Performance Testing Results – MMN Plate

Three coupons were tested such that crack lengths were measured before and after permanent crack detection. This provided a mechanical trends analysis to relate dCVM values to fatigue crack lengths. This data may allow for trend data to be used for reliability assessments.

CVM-C2MMN-7 Left Sensor						CVM-C2MMN-7 Right Sensor					
Cycles	Dynamic SIM1 (Pa)	1dCVM	2dCVM	Visual Total Crack Length Front (In)	EC Total Crack Length Back (In)	Cycles	Dynamic SIM2 (Pa)	1dCVM	2dCVM	Visual Total Crack Length Front (In)	EC Total Crack Length - Back (In)
16,311	12,000	0.4	1.5	0.191	0.181	16,311	3,624	0.3	0.0	0.189	0.169
16,864	14,000	0.9	1.7	0.204	0.220	16,864	7,566	1.1	0.0	0.193	0.213
17,583	15,500	1.4	2.7	0.210	0.252	17,583	11,630	2.1	0.2	0.207	0.240
18,356	16,500	1.8	3.5	0.236	0.283	18,356	14,123	3.6	0.0	0.224	0.244
18,827	16,913	2.4	2.8	0.250	0.295	18,827	15,000	4.3	0.1	0.234	0.279
19,307	17,250	2.5	2.8	0.256	0.295	19,307	15,778	5.1	0.7	0.240	0.291
19,979	17,600	2.9	6.5	0.259	0.321	19,979	16,604	6.9	1.3	0.254	0.299
20,983	17,958	3.5	3.5	0.307	0.343	20,983	17,329	8.2	2.4	0.287	0.327
21,992	18,230	4.2	3.6	0.338	0.372	21,992	17,782	9.8	3.6	0.311	0.354
23,328	18,596	12.4	9.0	0.376	0.406	23,328	18,244	15.9	4.7	0.349	0.386

dCVM Corresponding to Permanent Crack Detection is Highlighted (dCVM > 4.0)

CVM Performance Testing Results – MMN Plate

CVM-C2MMN-8 Left Sensor						CVM-C2MMN-8 Right Sensor					
Cycles	**Dynamic SIM1 (Pa)**	**1dCVM**	**2dCVM**	**Visual Total Crack Length Front (In)**	**EC Total Crack Length Back (In)**	**Cycles**	**Dynamic SIM2 (Pa)**	**1dCVM**	**2dCVM**	**Visual Total Crack Length Front (In)**	**EC Total Crack Length - Back (In)**
10,857	2,506	-0.2	0.1	0.175	0.224	10,857	14,000	1.2	0.5	0.188	0.252
11,733	10,105	1.3	0.1	0.201	0.248	11,733	16,000	1.7	1.2	0.205	0.274
12,679	14,470	3.4	0.0	0.224	0.276	12,679	17,000	2.5	1.6	0.231	0.305
13,057	15,500	4.2	0.0	0.228	0.280	13,057	17,243	2.7	1.7	0.235	0.317
13,969	16,808	6.4	0.3	0.258	0.319	13,969	17,750	3.4	2.8	0.278	0.341
15,039	17,763	8.4	1.3	0.299	0.354	15,039	18,100	3.7	2.8	0.298	0.370
15,725	18,357	25.2	3.6	0.307	0.374	15,725	18,280	4.9	3.7	0.321	0.409

CVM-C2MMN-9 Left Sensor						CVM-C2MMN-9 Right Sensor					
Cycles	**Dynamic SIM1 (Pa)**	**1dCVM**	**2dCVM**	**Visual Total Crack Length Front (In)**	**EC Total Crack Length Back (In)**	**Cycles**	**Dynamic SIM2 (Pa)**	**1dCVM**	**2dCVM**	**Visual Total Crack Length Front (In)**	**EC Total Crack Length - Back (In)**
12,561	5,094	0.1	-0.1	0.196	0.238	12,561	12,000	1.3	2.4	0.212	0.228
13,048	10,003	0.5	0.0	0.214	0.258	13,048	14,000	1.9	1.6	0.222	0.256
13,920	14,684	2.0	0.0	0.239	0.276	13,920	16,000	2.8	1.6	0.234	0.280
14,878	16,750	3.1	0.6	0.269	0.309	14,878	17,000	3.6	3.7	0.248	0.319
15,316	17,154	3.7	1.2	0.281	0.313	15,316	17,350	4.5	3.9	0.271	0.333
15,590	17,400	4.1	1.5	0.292	0.325	15,590	17,491	4.6	4.5	0.281	0.346
16,640	17,885	6.1	2.8	0.324	0.360	16,640	17,937	6.0	6.6	0.311	0.370
17,624	18,230	9.8	4.7	0.357	0.400	17,624	18,220	8.0	7.3	0.354	0.404
18,585	18,884	185.0	104.0	0.430	0.437	18,585	18,572	21.0	11.7	0.417	0.439

dCVM Corresponding to Permanent Crack Detection is Highlighted (dCVM > 4.0)

POD Analysis Using Standard Hit-Miss Methodology – MM Nutplate

Actual Test Hit/Miss Data Acquired from 19 Sensors (65 data points)

Sikorsky Mickey Mouse Nut Plate CVM Sensor Performance Tests

Specimen	Eddy Current Crack Length at CVM (in)	Hit (1) or Miss (0)
CVM-C2MMN-1-L	0.138	1
CVM-C2MMN-1-R	0.111	1
CVM-C2MMN-2-L	0.180	1
CVM-C2MMN-2-R	0.125	1
CVM-C2MMN-3-L	0.135	1
CVM-C2MMN-3-R	0.242	1
CVM-C2MMN-4-L	0.278	1
CVM-C2MMN-5-L	0.220	1
CVM-C2MMN-5-R	0.146	1
CVM-C2MMN-6-L	0.129	1
CVM-C2MMN-6-R	0.181	1
CVM-C2MMN-7-L	0.081	0
CVM-C2MMN-7-L	0.120	0
CVM-C2MMN-7-L	0.152	0
CVM-C2MMN-7-L	0.183	0
CVM-C2MMN-7-L	0.195	0
CVM-C2MMN-7-L	0.195	0
CVM-C2MMN-7-L	0.221	0
CVM-C2MMN-7-L	0.243	0
CVM-C2MMN-7-L	0.272	1
CVM-C2MMN-7-L	0.306	1
CVM-C2MMN-7-R	0.059	0

Sikorsky Mickey Mouse Nut Plate CVM Sensor Performance Tests

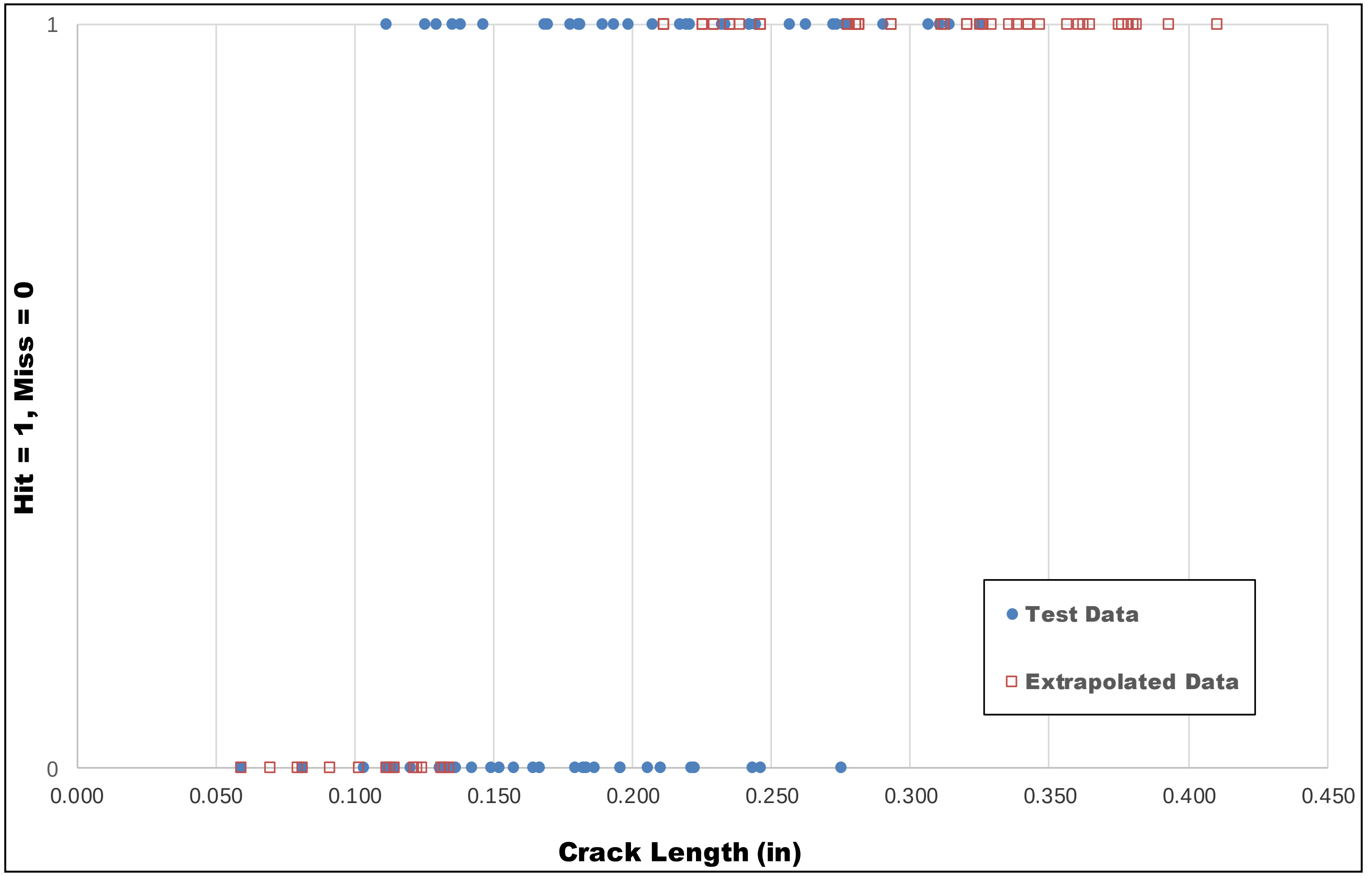
Specimen	Eddy Current Crack Length at CVM (in)	Hit (1) or Miss (0)
CVM-C2MMN-7-R	0.103	0
CVM-C2MMN-7-R	0.130	0
CVM-C2MMN-7-R	0.134	0
CVM-C2MMN-7-R	0.169	1
CVM-C2MMN-7-R	0.181	1
CVM-C2MMN-7-R	0.189	1
CVM-C2MMN-7-R	0.217	1
CVM-C2MMN-7-R	0.244	1
CVM-C2MMN-7-R	0.276	1
CVM-C2MMN-8-L	0.112	0
CVM-C2MMN-8-L	0.136	0
CVM-C2MMN-8-L	0.164	0
CVM-C2MMN-8-L	0.168	1
CVM-C2MMN-8-L	0.207	1
CVM-C2MMN-8-L	0.242	1
CVM-C2MMN-8-L	0.262	1
CVM-C2MMN-8-R	0.157	0
CVM-C2MMN-8-R	0.179	0
CVM-C2MMN-8-R	0.210	0
CVM-C2MMN-8-R	0.222	0
CVM-C2MMN-8-R	0.246	0
CVM-C2MMN-8-R	0.275	0

Sikorsky Mickey Mouse Nut Plate CVM Sensor Performance Tests

Specimen	Eddy Current Crack Length at CVM (in)	Hit (1) or Miss (0)
CVM-C2MMN-8-R	0.314	1
CVM-C2MMN-9-L	0.111	0
CVM-C2MMN-9-L	0.131	0
CVM-C2MMN-9-L	0.149	0
CVM-C2MMN-9-L	0.182	0
CVM-C2MMN-9-L	0.186	0
CVM-C2MMN-9-L	0.198	1
CVM-C2MMN-9-L	0.233	1
CVM-C2MMN-9-L	0.273	1
CVM-C2MMN-9-L	0.310	1
CVM-C2MMN-9-R	0.114	0
CVM-C2MMN-9-R	0.142	0
CVM-C2MMN-9-R	0.166	0
CVM-C2MMN-9-R	0.205	0
CVM-C2MMN-9-R	0.219	1
CVM-C2MMN-9-R	0.232	1
CVM-C2MMN-9-R	0.256	1
CVM-C2MMN-9-R	0.290	1
CVM-C2MMN-9-R	0.325	1
CVM-C2MMN-10-L	0.193	1
CVM-C2MMN-10-R	0.177	1

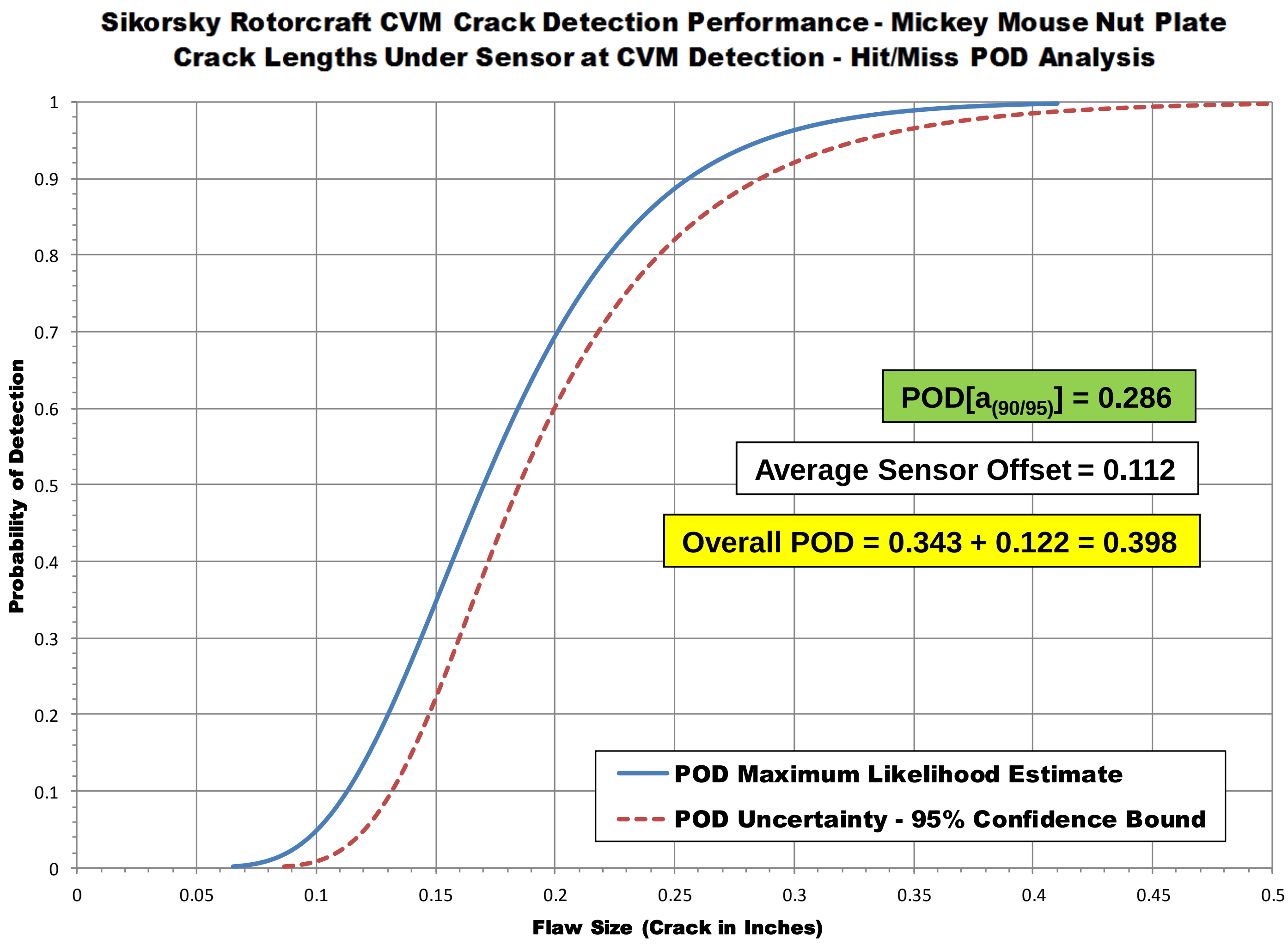
POD Analysis Using Standard Hit-Miss Methodology – MM Nutplate

Hit-Miss data was compiled using crack CVM detection length from each test along with missed crack detections (lengths) below CVM detection level & hit crack detections (lengths) above the CVM detection level.



65 Acquired Hit/Miss Data Points Plus Extrapolated Hit/Miss Data Points on Either Side to Produce a Complete POD Curve Using Extreme Crack Lengths (High and Low)

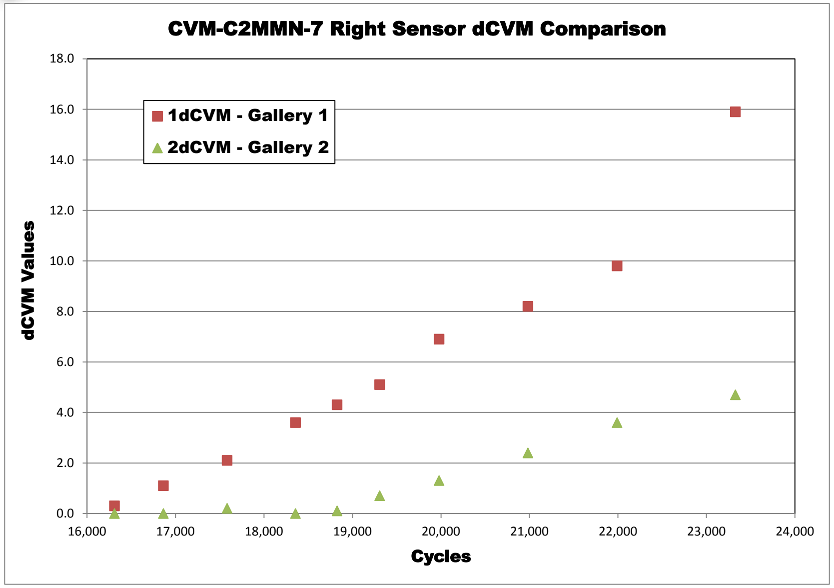
POD Analysis Using Standard Hit-Miss Methodology – MM Nutplate

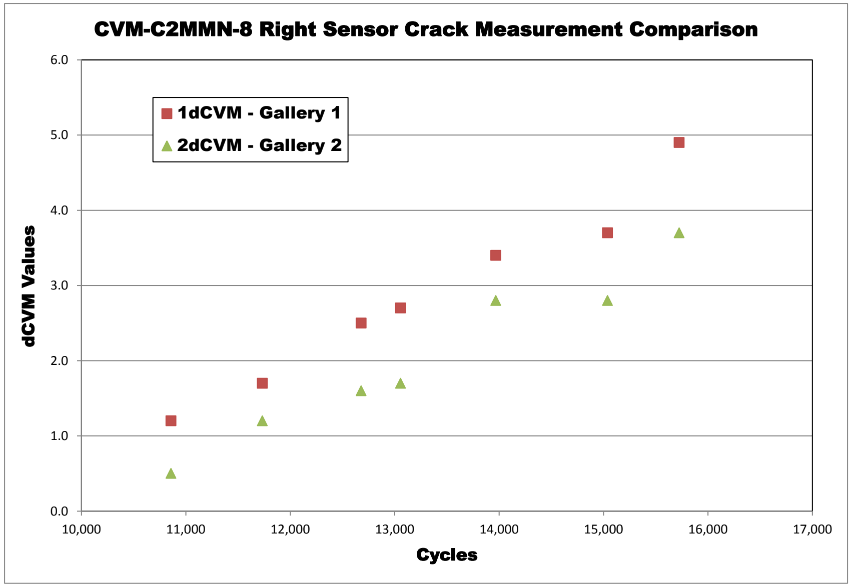


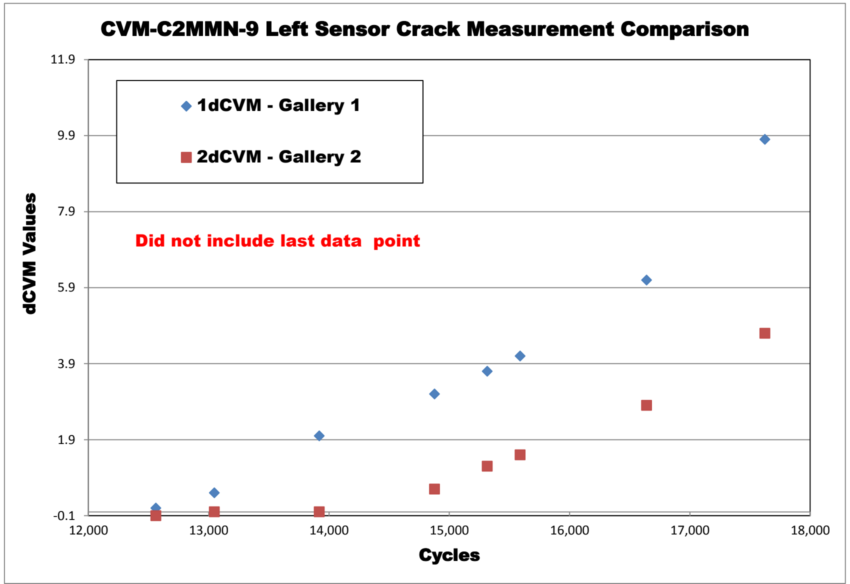
65 Acquired Hit/Miss Data Points Plus Extrapolated Hit/Miss Data Points on Either Side to Produce a Complete POD Curve Using Extreme Crack Lengths (High and Low)

CVM Performance Testing Results – Mechanical Trend Assessment

dCVM Increase with Fatigue Cycles (Crack Growth)



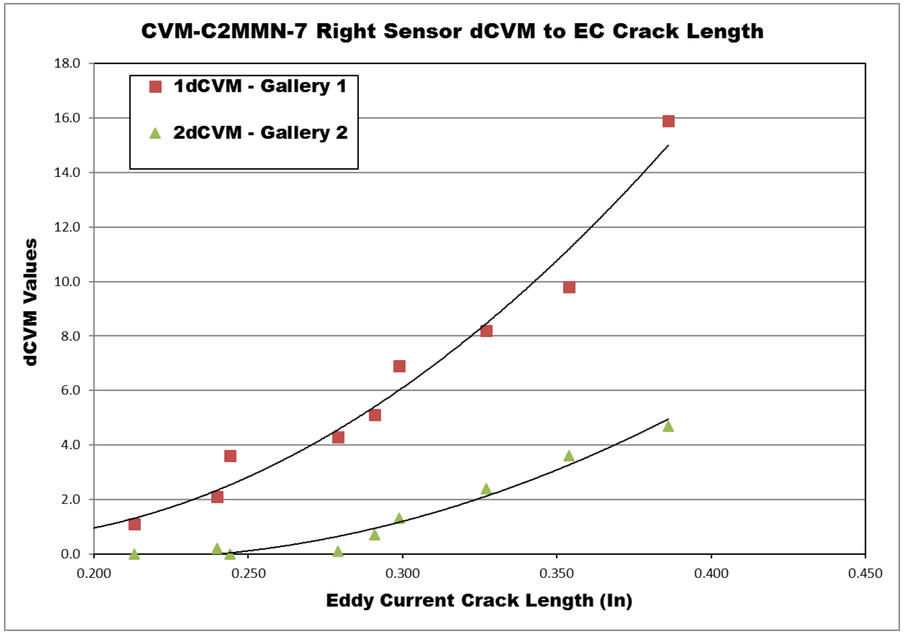


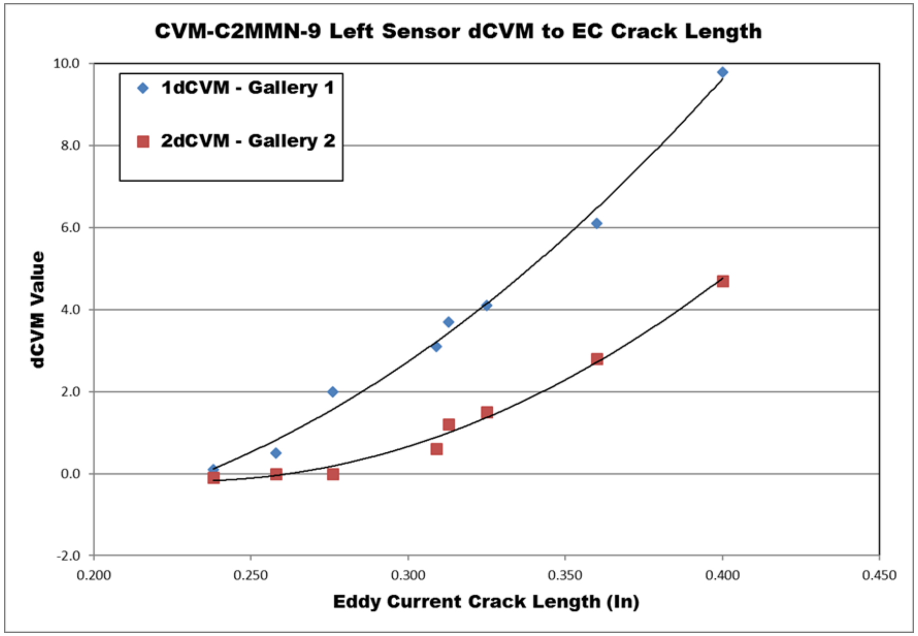


CVM Performance Testing Results – MMN Plate

Coupons CVM-C2MMN-7, 8 & 9 were tested such that crack lengths were measured before and after permanent crack detection. This provided a mechanical trends analysis to relate dCVM values to fatigue crack lengths. This data may allow for trend data to be used for reliability assessments.

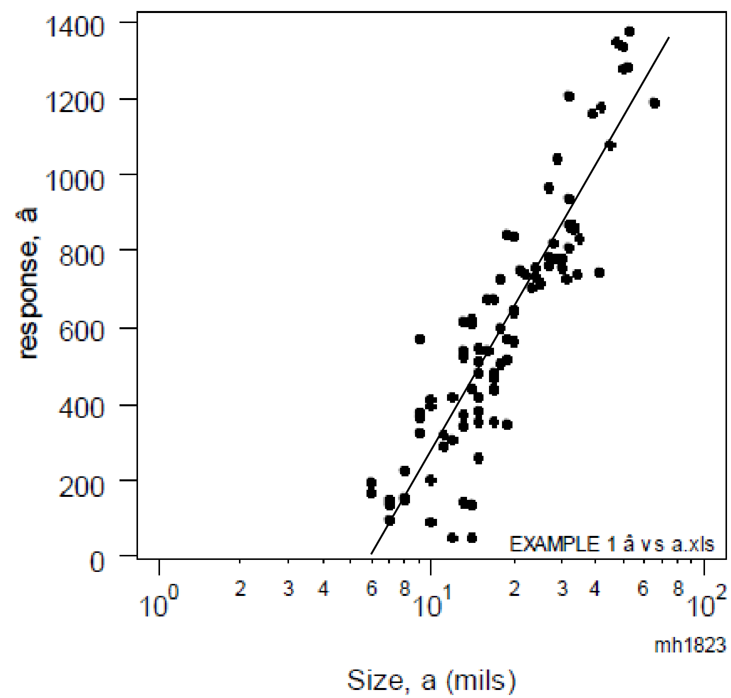
CVM Sensor Mechanical Trend Assessment





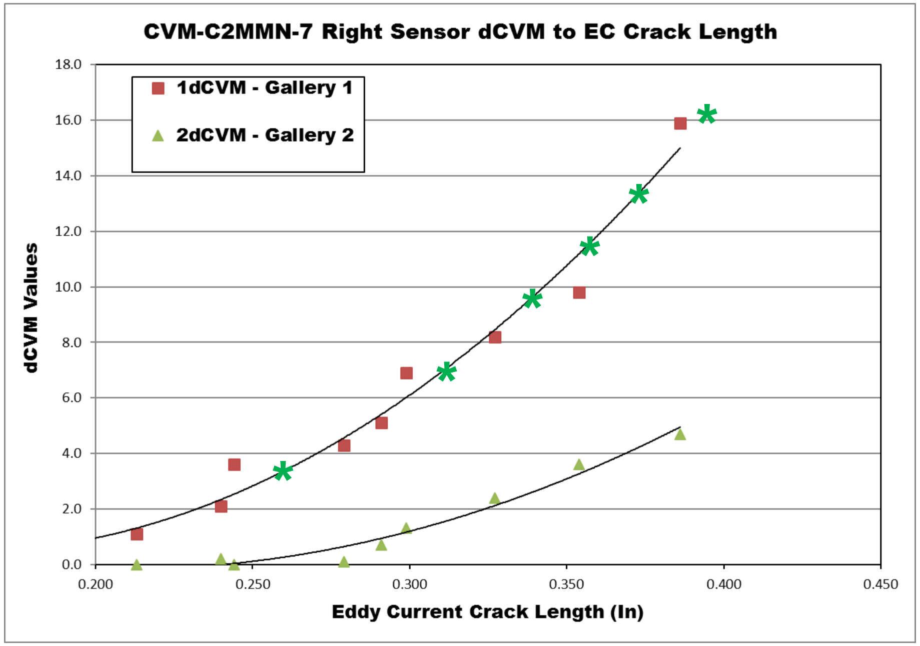
POD Analysis Using Standard a vs. â Methodology (Mil-HDBK-1823)

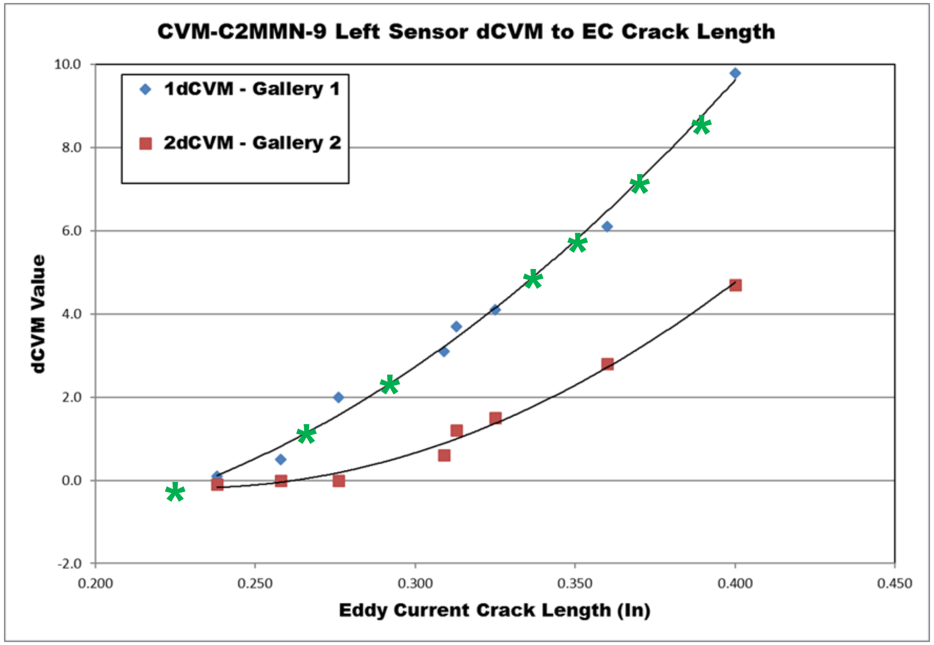
- The SHM system must produce output for damage detection that can be reduced to a quantitative signal, ***â***
- Use of a critical SHM system response can contain more information, and the amplitude, ***â***, of the output makes it possible to extract other POD(a) estimates that could have narrower confidence bounds; ***â*** is the system output and ***a*** is the size of the damage (***â vs a*** POD Model)
- POD(a) depends on a reasonable ***â vs a*** model - data plot of *â vs log(a)* should reveal a linear relationship. Describes the expected response, ***â***, at any given size, a. Notice that it provides a reasonable summary of the data – the line is straight; the data are straight. The scatter is consistent and not wider at one end or the other.
- Must consider the S/N ratio which includes the scatter in the results (note similarity in OSTI)



POD Analysis Using Standard a vs. â Methodology (Mil-HDBK-1823)

- **CVM system response data dCVM (*â*) vs. crack length (*a*) was acquired during testing that included measurements before, during and after SHM crack detection**
- **Convergence observed as additional data points were acquired by interpolating between the measured points in the dCVM vs Crack Length plots**





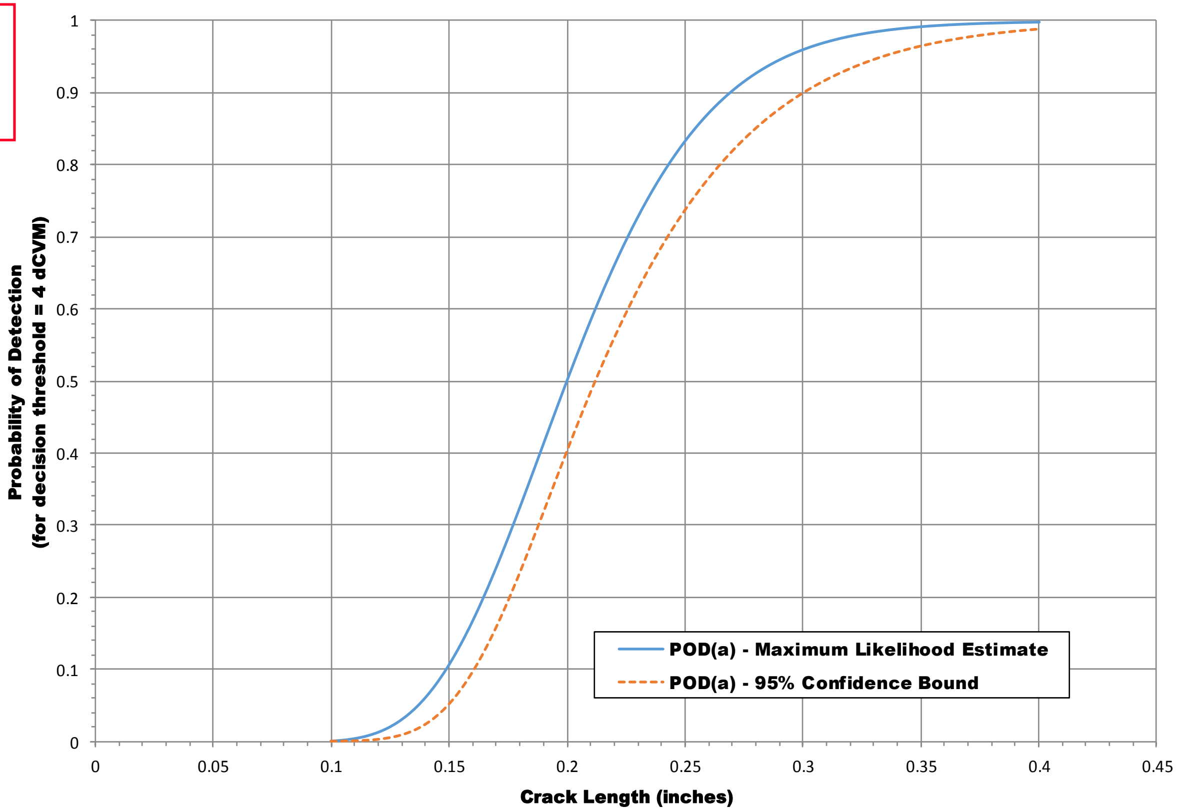
POD Analysis Using Standard a vs. â Methodology (Mil-HDBK-1823)

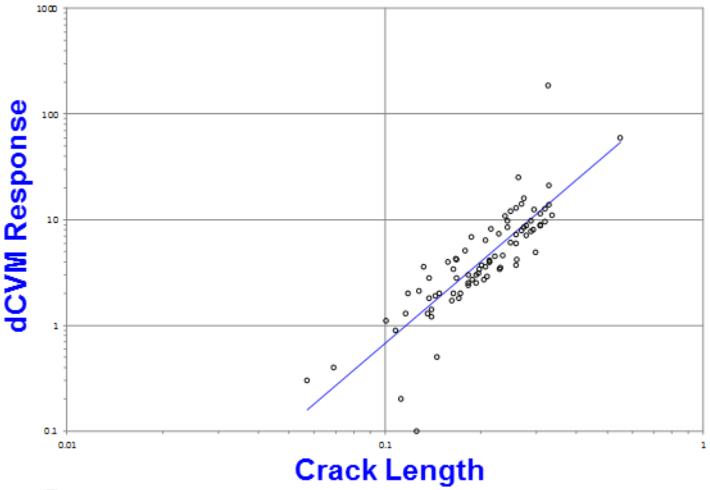
52 Acquired Data Points Plus 30 Extrapolated Data Points

POD[$a_{(90/95)}$] = 0.300

Average Sensor Offset = 0.112

Overall POD = 0.343 + 0.122 = 0.412



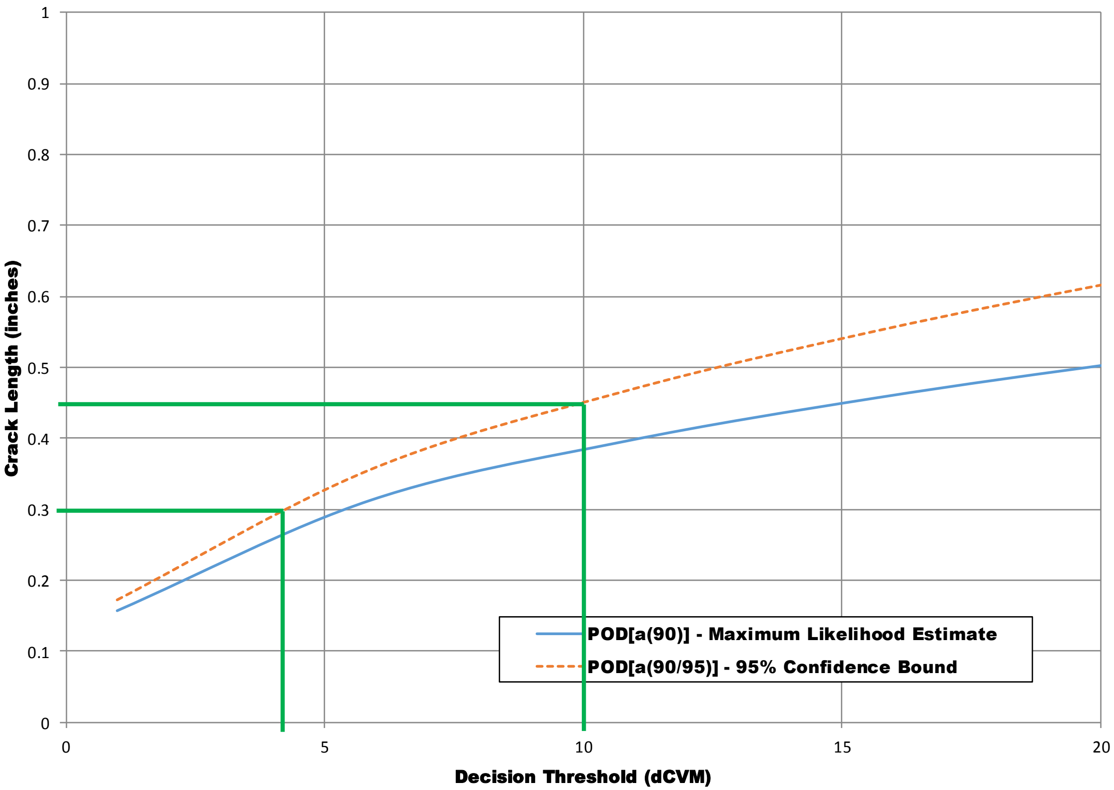


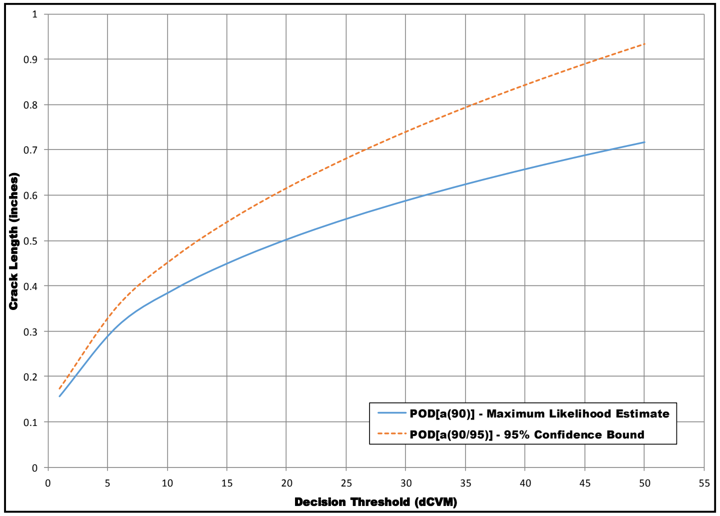
Data check – linear response on a log-log scale

Note: MM nutplate data

Estimated $POD_{(90/95)}$ Values for Adjusted â Decision Thresholds (a vs. â methodology)

52 Acquired Data Points Plus 30 Extrapolated Data Points



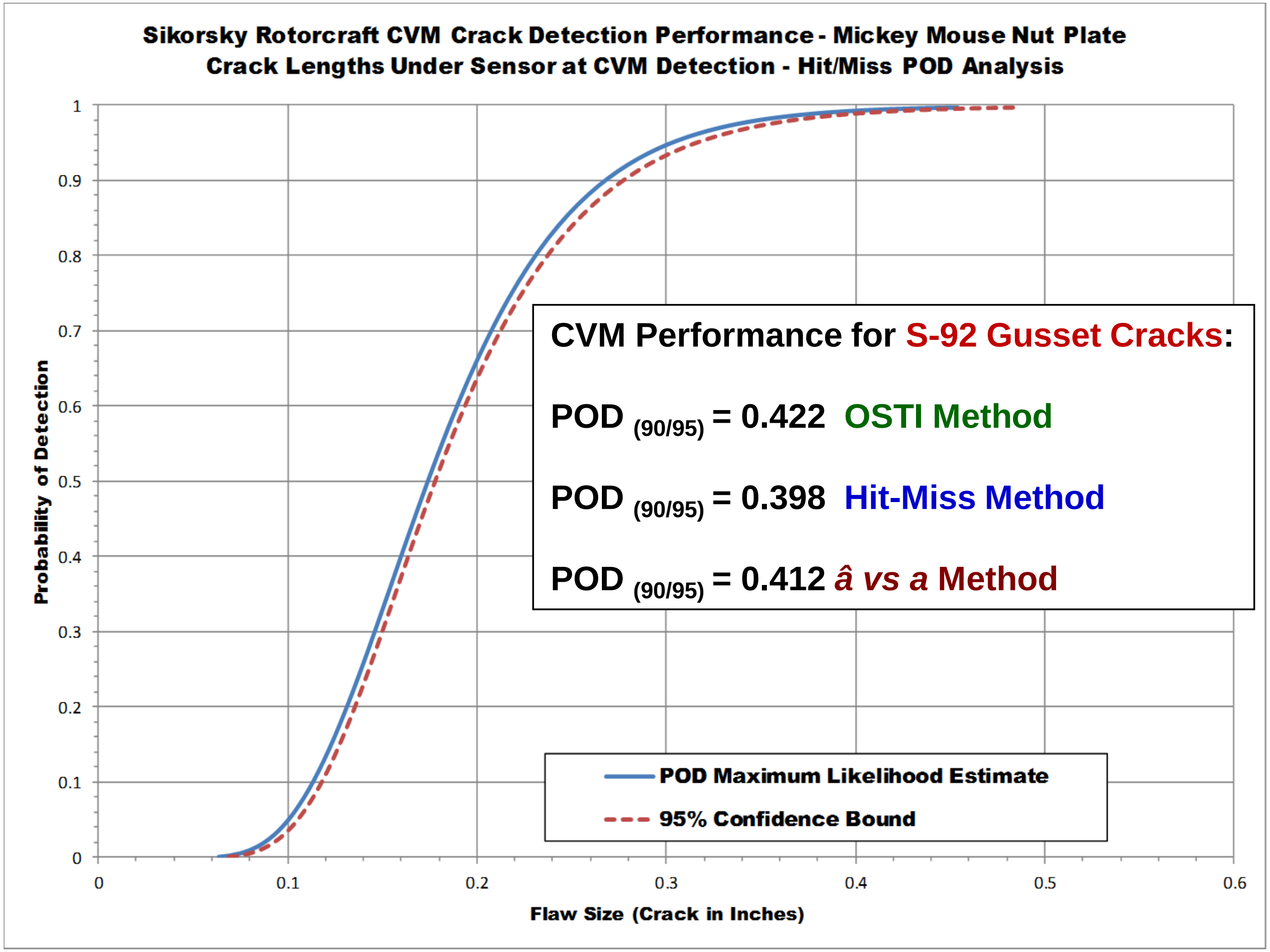


Estimate POD Performance of SHM System if Detection Threshold is Changed

dCVM(detection) = 4 → $POD[a_{(90/95)}] = 0.300$"
dCVM(detection) = 10 → $POD[a_{(90/95)}] \approx 0.450$"

Note: MM nutplate data

CVM Performance Testing Results –
Comparison of OSTI, Hit-Miss, and a vs. â Methodologies
MM Nutplate on S-92 Frame Gusset



Overall CVM Performance – POD for CVM Monitoring of Cracks in S-92 Frame Gusset

CVM Performance for **Straight Nutplate**:

POD $_{(90/95)}$ = 0.447 OSTI method

POD $_{(90/95)}$ = 0.416 Hit-Miss method

CVM Performance for **Mickey Mouse Nutplate**:

POD $_{(90/95)}$ = 0.422 OSTI method

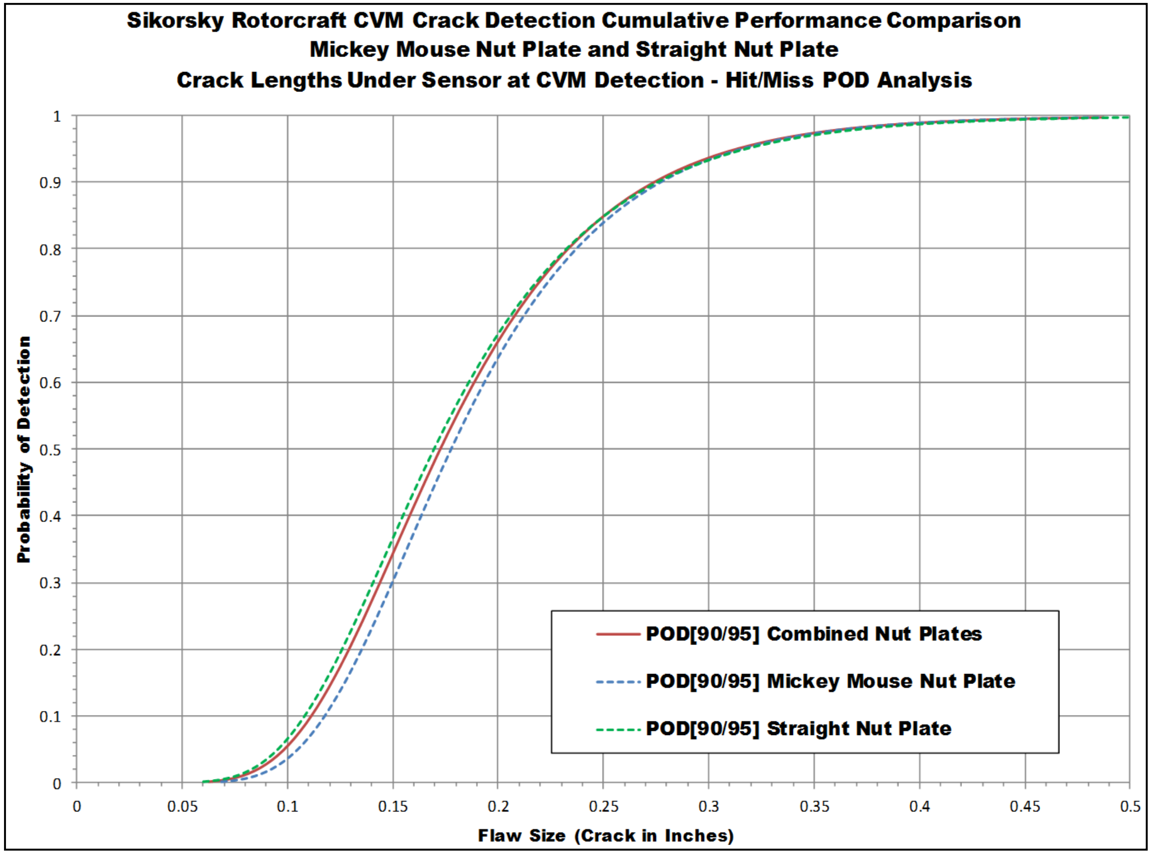
POD $_{(90/95)}$ = 0.398 Hit-Miss method

POD $_{(90/95)}$ = 0.412 *â vs a* Method

Overall CVM Performance for **Both Nutplates**:

POD $_{(90/95)}$ = 0.412 OSTI method

POD $_{(90/95)}$ = 0.401 Hit-Miss method



Note: sensor offset values (distance from crack origin to sensor engagement) must be added to POD levels plotted above)

- Improvements in overall POD for OSTI method is due to increase in data points and corresponding lowering of K value
- Improvements in overall POD for H-M method is due to additional, consistent data & corresponding improvement in POD curve fit

Conclusions

- SHM systems can be used to assess the structural integrity (or deviations from optimum performance) of large structures such as aircraft, bridges, pipelines, large vehicles
- Methods to statistically quantify the performance of SHM systems are needed to properly deploy SHM solutions
- Several different methods for possible use in quantifying the damage detection capability (POD) of SHM systems were compared: OSTI, Log Regression, and *a vs. â* models → Need assist from "Repeated Measures" models (MAPOD)
- OSTI method can require less data but a "penalty" can appear in the Probability Factor (K) & standard deviation of the data (S); showed viability of OSTI for a CVM sensor detecting a crack which is propagating in a known/consistent direction
- A complete understanding of the parameters involved in the SHM systems' response & the effect of those parameters on the resulting POD is necessary to properly apply these POD models
  - flaw size, shape, orientation and location relative to the sensors,
  - structural configuration,
  - variability in the damage,
  - residual strains & environmental variables
- Looking forward, large databases on sensor response/performance in multiple applications may help to determine if certain assumptions can be made & how to apply them – arrive at conservative envelope of POD

Comparison of Multiple Statistical Methods for Calculating the Probability of Detection from SHM Systems