Preparing Structural Health Monitoring Systems for Real-Life Applications

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multi-functional materials
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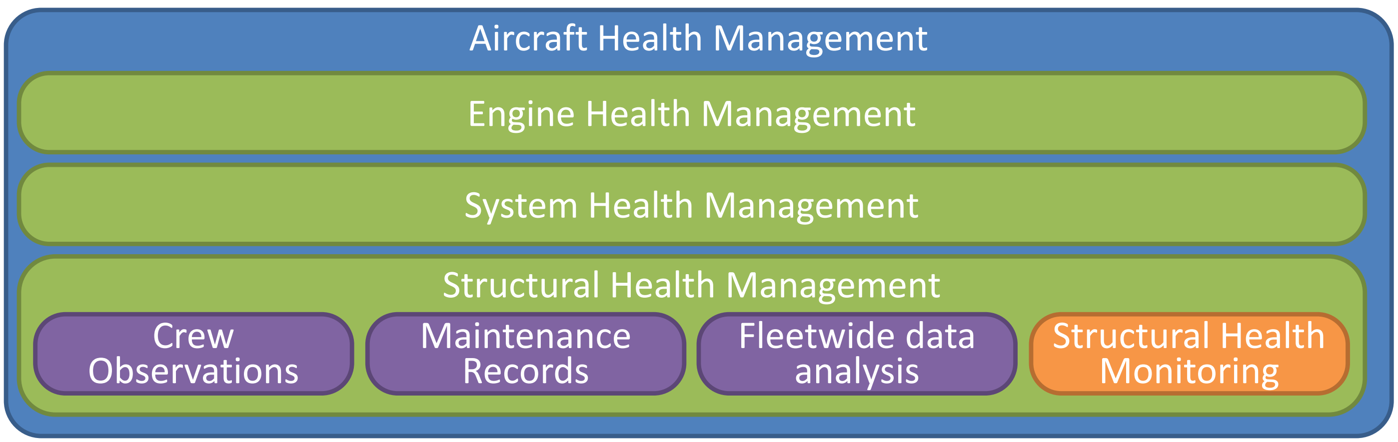
What is SHM?

- Structural Health Monitoring (SHM)
  - ➢ Defined by Aerospace Industry Steering Committee for SHM (AISC-SHM) in ARP-6461 (also A4A MSG-3)
    - — "The process of acquiring & analyzing data from on-board sensors to evaluate the health of a structure"
  - ➢ Defined by United States Air Force (USAF) in MIL-STD-1530D
    - — "A nondestructive inspection process or technique that uses in-situ sensing devices to detect damage"
  - ➢ Sensors that are PERMANENTLY ATTACHED that can be used to guide, supplement or replace NDT
    - — Could include presently installed sensors and/or new application-specific sensors



How does SHM Differ from NDT?

- Nondestructive Testing (NDT): examination of material to determine if damage is present
  - Can be visual, but usually involves handheld probes & hardware
  - Typically requires a high degree of human interaction by trained & certified experts
  - Inspections are performed locally, focused on specific areas
  - Requires access to area of interest, often compelling tear-down
  - Must not adversely effect material in any way

- SHM: in-situ sensing allows for rapid, remote & on-demand condition assessments
  - Minimize human factors with automated data collection & analysis
  - Can cover large areas quickly (global detection)
  - Can provide greater vigilance/sensitivity in key areas (local detection)
  - Overcome accessibility, and some complex geometry & depth limitations
  - Eliminate costly & potentially detrimental disassembly (collateral damage)

What are the Consequences of these Differences?

- SHM still requires the same detection sensitivity quantification as traditional NDT
  - ➢ Probability of Detection (POD) & Probability of False Alarm (PFA)
  - ➢ Statistical testing could be much more expensive for SHM because sensors are permanently installed
    - — Processes like described in MIL-HDBK-1823A only allow 1 data point per specimen due to independence assumption
    - — Sensor durability also becomes a major factor, must be considered as part of the Design of Experiment (DOE)

- Must also qualify airworthiness similar to any airborne equipment
  - ➢ Environmental (range of typical operating conditions does not affect performance)
  - ➢ Mechanical (will not become a projectile under shock/impact/vibration loading)
  - ➢ Electrical (will not interference with other on-board equipment)
  - ➢ Materials (many are not allowed for certain applications, e.g. silicone, PVC, Kapton; space outgassing)
  - ➢ Software (special considerations if system is powered in flight vs just ground-based collection)
  - * These qualification requirements apply to <u>sensors</u>, <u>hardware</u>, <u>cables,</u> <u>connectors</u> & <u>epoxies/fasteners</u>

Airworthiness Standards are Straightforward

MIL-STD-810H: Military Environmental Airworthiness	
500.6	Low Pressure (Altitude)
501.6	High Temperature
502.6	Low Temperature
503.6	Temperature Shock
504.2	Contamination by Fluids
505.6	Solar Radiation (Sunshine)
506.6	Rain
507.6	Humidity
508.7	Fungus
509.6	Salt Fog
510.6	Sand and Dust
511.6	Explosive Atmosphere
512.6	Immersion
513.7	Acceleration
514.7	Vibration
515.7	Acoustic Noise
516.7	Shock
517.2	Pyroshock
518.2	Acidic Atmosphere
519.7	Gunfire Shock
520.4	Temperature, Humidity, Vibration, & Altitude
521.4	Icing/Freezing Rain
522.2	Ballistic Shock
523.4	Vibro-Acoustic/Temperature
524.1	Freeze / Thaw

MIL-STD-461G: Military Electromagnetic Interference	
CE101	Conducted Emissions, Audio Frequency Currents, Power Leads
CE102	Conducted Emissions, Radio Frequency Potentials, Power Leads
CS101	Conducted Susceptibility, Power Leads
CS114	Conducted Susceptibility, Bulk Cable Injection
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables & Power Leads
CS117	Conducted Susceptibility, Lightning Induced Transients, Cables & Power Leads
CS118	Conducted Susceptibility, Personnel Borne Electrostatic Discharge
RE101	Radiated Emissions, Magnetic Field
RE102	Radiated Emissions, Electric Field
RS101	Radiated Susceptibility, Magnetic Field
RS103	Radiated Susceptibility, Electric Field

RTCA DO-160 / EUROCAE ED-14 (rev G change 1)	
4.0	Temperature Altitude
5.0	Temperature Variation
6.0	Humidity
7.0	Shock & Crash safety
8.0	Vibration
9.0	Explosion proofness
10.0	Water proofness
11.0	Fluids susceptibility
12.0	Sand & Dust
13.0	Fungus Resistance
14.0	Salt & Fog
15.0	Magnetic effect
16.0	Power input
17.0	Voltage spike
18.0	Audio Frequency Conducted Susceptibility
19.0	Induced signal susceptibility
20.0 & 21.0	RF emission & susceptibility
22.0 & 23.0	Lightning susceptibility
24.0	Icing
25.0	ESD
26.0	Flammability

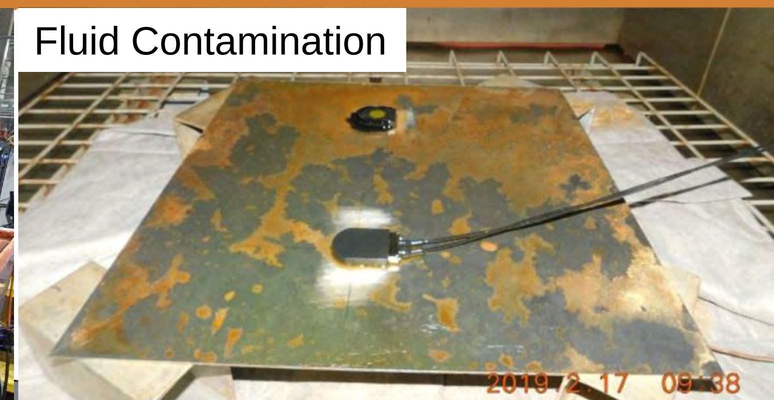
Only defines testing methods/materials/setup
Suggests limits, often application-specific

Examples of Airworthiness Qualification Testing

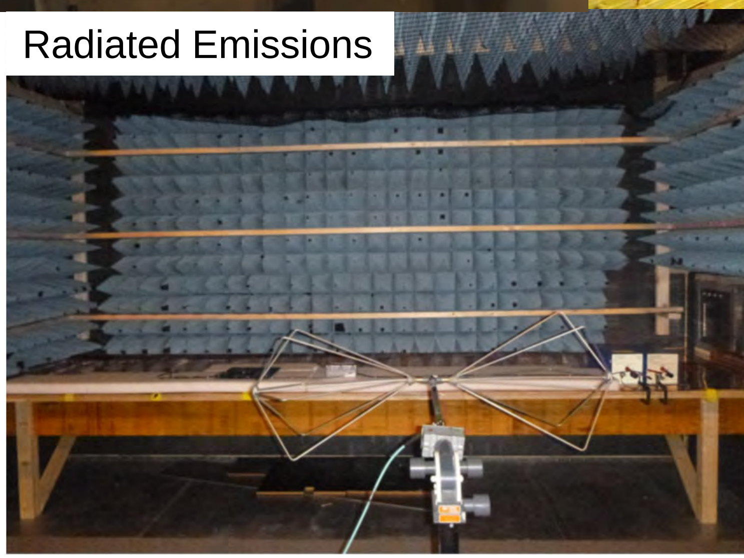
Temperature

Salt Fog

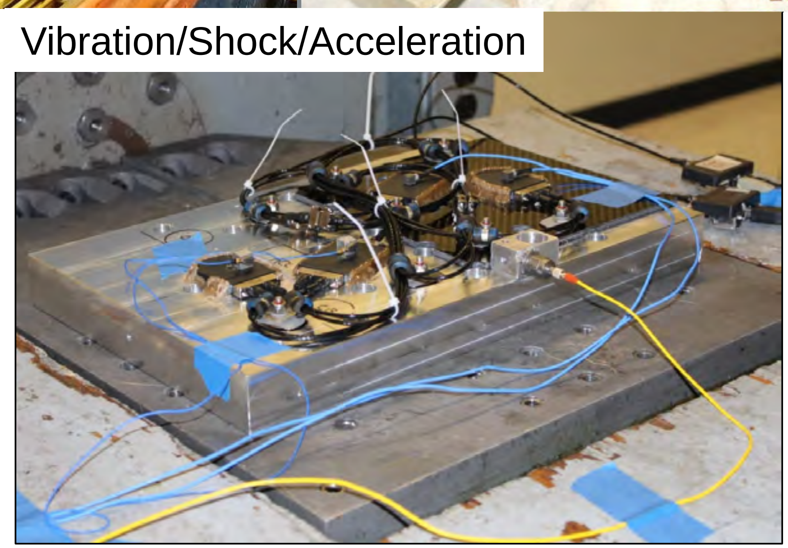
Fluid Contamination



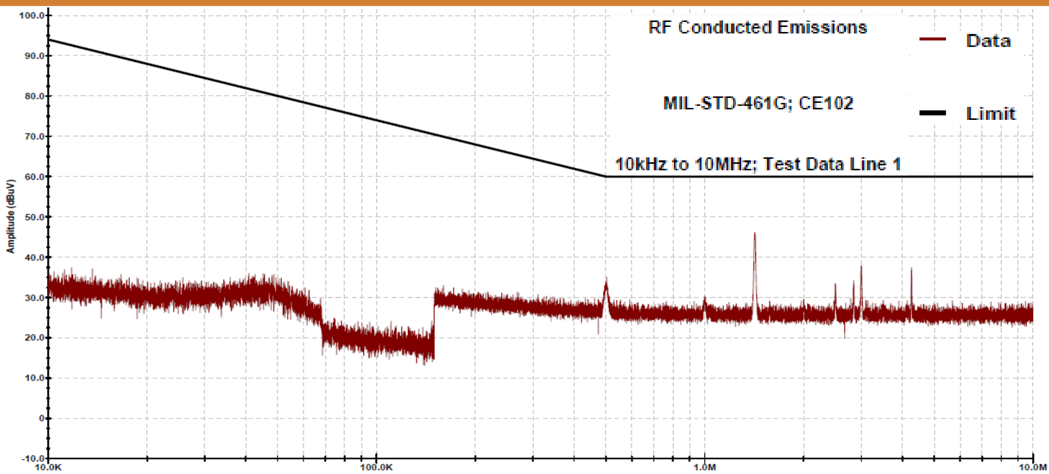
Radiated Emissions

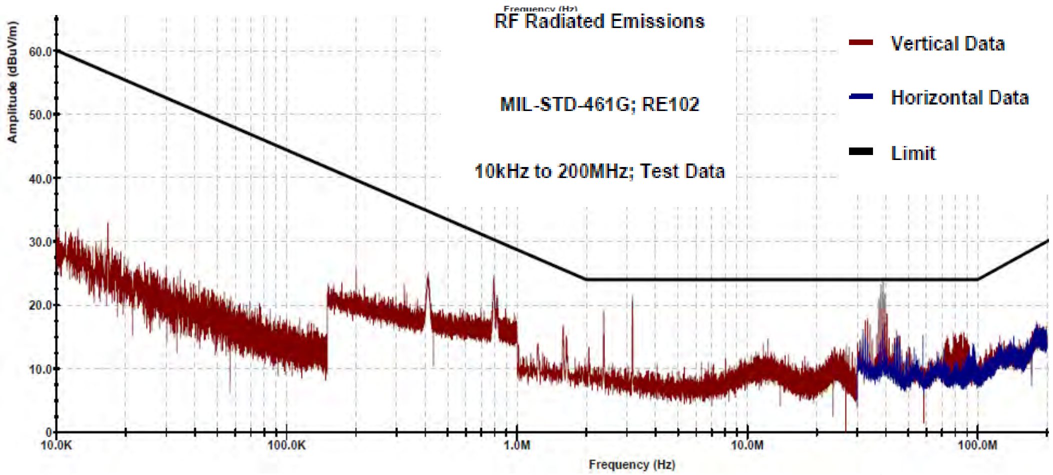


Vibration/Shock/Acceleration



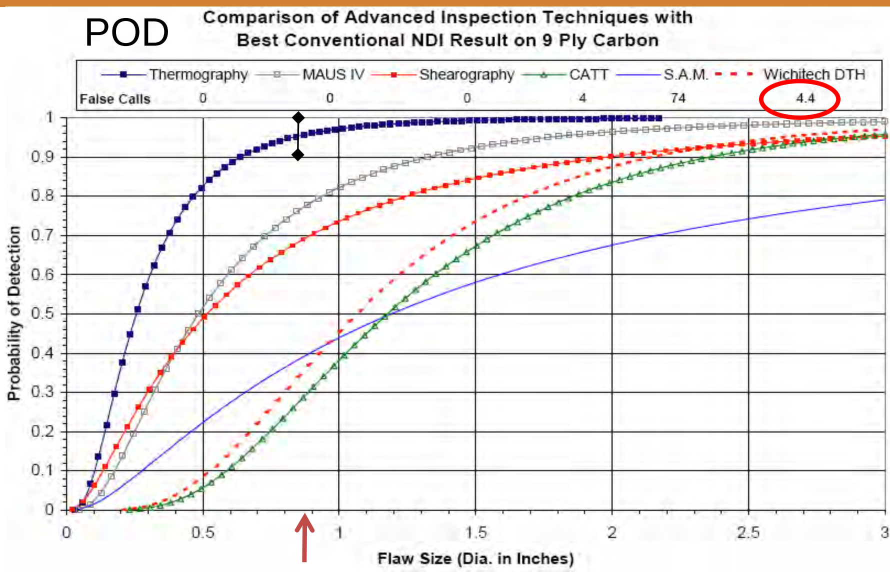
Examples of Airworthiness Qualification Results

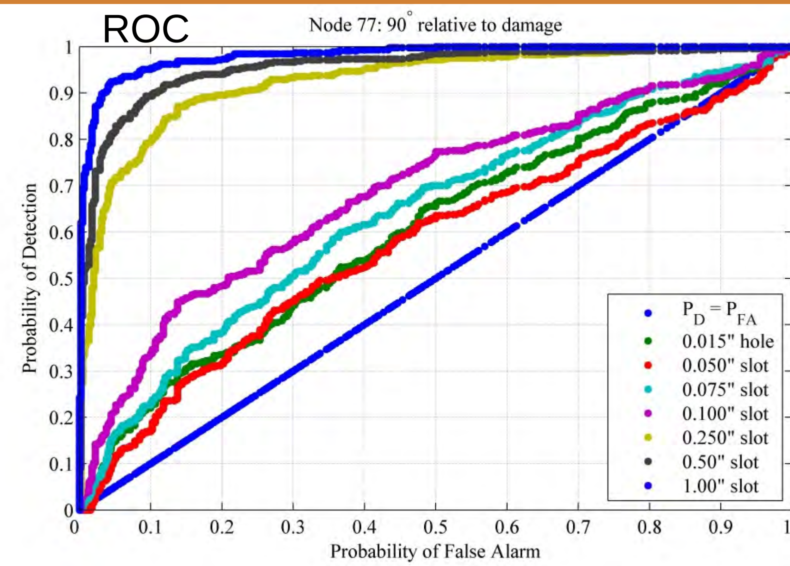




Test Name	MIL-STD Document & Method No.	Test Procedure Document & Section	Result	Appendix Reference
Temperature (High)	MIL-STD-810G Method No. 501.6	E-7712-9 Section 7.4	Pass	B
Temperature (Low)	MIL-STD-810G Method No. 502.6	E-7712-9 Section 7.4	Pass	C
Thermal Shock	MIL-STD-810G Method No. 503.5	E-7712-2 Section 7.6	Pass	F
Vibration	MIL-STD-810G Method No. 514.7	E-7712-9 Section 7.5	Pass	D
Crash Hazard Shock	MIL-STD-810G Method No. 516.7	E-7712-9 Section 7.6	Pass	E
Humidity	DO-160F Section 6	E-7712-2 Section 7.9	Pass	G
Altitude	MIL-STD-810G Method No. 500.6	E-7712-2 Section	Pass	H
Salt Fog	DO-160F Section 14	E-7712-2 Section 7.10	Pass	N/A
Contamination by Fluids	MIL-STD-810G Method No. 504.1	E-7712-2 Section 7.11	Pass	N/A
Electrical Bonding	*MIL-STD-464C Paragraph 5.11*	*E-7712-10 Section 7.5*	Pass	N/A

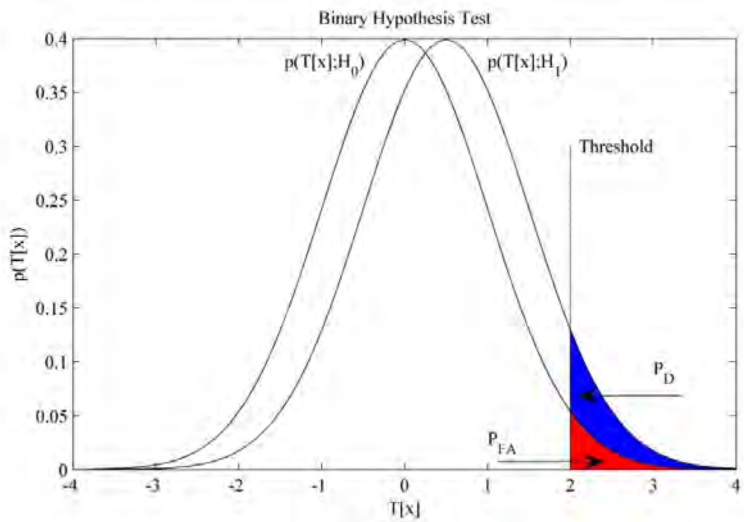
Probability of Detection (POD) Quantification not as Straightforward

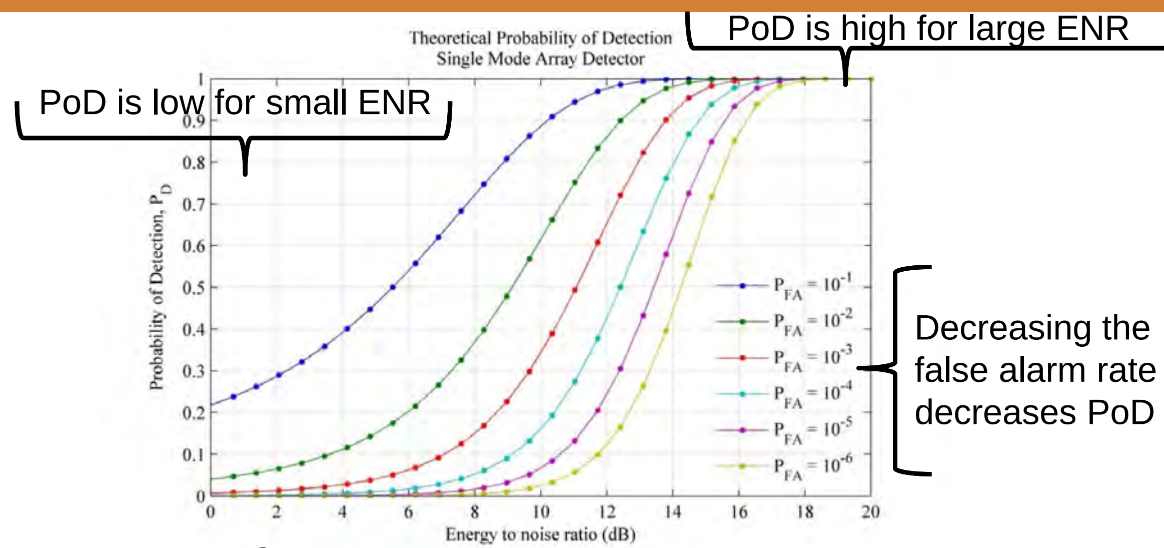




- **MIL-HDBK-1823A most common precedent to assess sensor detection capabilities**
  - Key metric is $a_{90/95}$ – smallest flaw detected with 90% probability and 95% confidence
  - Must keep probability of false positive low too (i.e. minimize incorrect indications)
  - Must incorporate <u>sensor durability</u> under operating conditions through Design of Experiment (DOE)
- **ROC (Receiver Operating Characteristic) curve can be used for fixed flaw sizes**

Signal Processing of Sensor Data





- **Process sensor data with a detector T[x] derived from assumed signal model**
  - **Binary Hypothesis Test: decide if damage is present (H1) or not (H0)**
    - If T[x] > threshold then damage is present
    - If T[x] < threshold then damage in not present
  - **False alarm rate of 10^{-3}: 1 of 1000 undamaged tests is mistakenly indicated as damaged**
- **PoD is a function of energy of scattered signal versus strength of noise**
  - **Energy to Noise Ration (ENR) related to flaw size, distance to damage for global methods**

Measuring POD

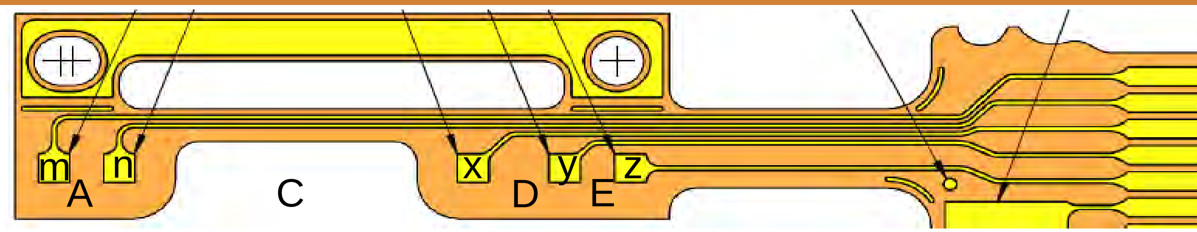
- MIL-HDBK-1823A references call out test matrix
  - Largely statistically based, software provides results based on data
  - Need statically significant sample size (based on slope of POD curve)
  - Need to explicitly control variability
- "Statistically significant" is somewhat subjective
  - HDBK essentially says to consult a statistician, suggests 40-60 tests
  - Multiple tests on the same specimen, even if progressive, does not count
  - Paper from Rutgers/UTRC provides iterative approach to minimizing
  - <u>Model-Assisted POD (MAPOD)</u> has been advocated for reducing tests & expanding applicability
- Variable tracking is essential
  - Need to define all inspection variable & possible ranges
  - Conduct DOE to determine which variables affect POD
  - Randomly introduce all significant variable combinations into POD test matrix

SHM Implications on POD

- Economically impractical to obtain $a_{90/95}$ for SHM using traditional approaches
  - ➢ Expensive due to permanent sensor installation, need for many specimens (60+)
  - ➢ Do not allow for repeated inspections as flaw grows (presumes independence of data)
  - ➢ DOE has the potential to introduce many extra variables to account for durability/ageing
- Fixed 90% POD requirement is somewhat outdated (but requires customer education)
  - ➢ Meant to maximize time between inspection intervals, but SHM can inspect more frequently at no cost
  - ➢ OEM sets for failure critical areas since NDI POD is constant regardless of application location
  - ➢ Global SHM methods have POD that will change as a function of distance → POD distribution
- Traditional 95% confidence interval is driving parameter for POD test matrix
  - ➢ Key is to establish the same confidence interval with fewer physical tests
  - ➢ Achieved through weighing "repeated measurements", Monte Carlo methods & models/simulation
  - ➢ Desire is to maintain (or lower) overall risk of failure while leveraging SHM advantages

Design of Experiment (DOE) Test Matrix

- **Temperature testing (6 of each)**
  - Elevated temperature (25, 40, 65 °C)
  - Reduced temperature (25, 0, -20 °C)
- **Strain testing (6 of each)**
  - Tensile strain (0, 1500, 3000 με)
  - Compressive strain (0, -1500, -3000 με)
- **Humidity (0, 50, 100%RH) (6 of each)**
- **Ageing Study (6 of each)**
  - Natural ageing (over 3 weeks)
  - Ageing under vacuum (1 Bar)
  - Ageing under elevated temperature (65 °C)
  - Ageing under static strain (3000 με)
  - Ageing under fatigue loading (1500 με)
- **Hardware Study (6x6 matrix of sensors & hardware)**



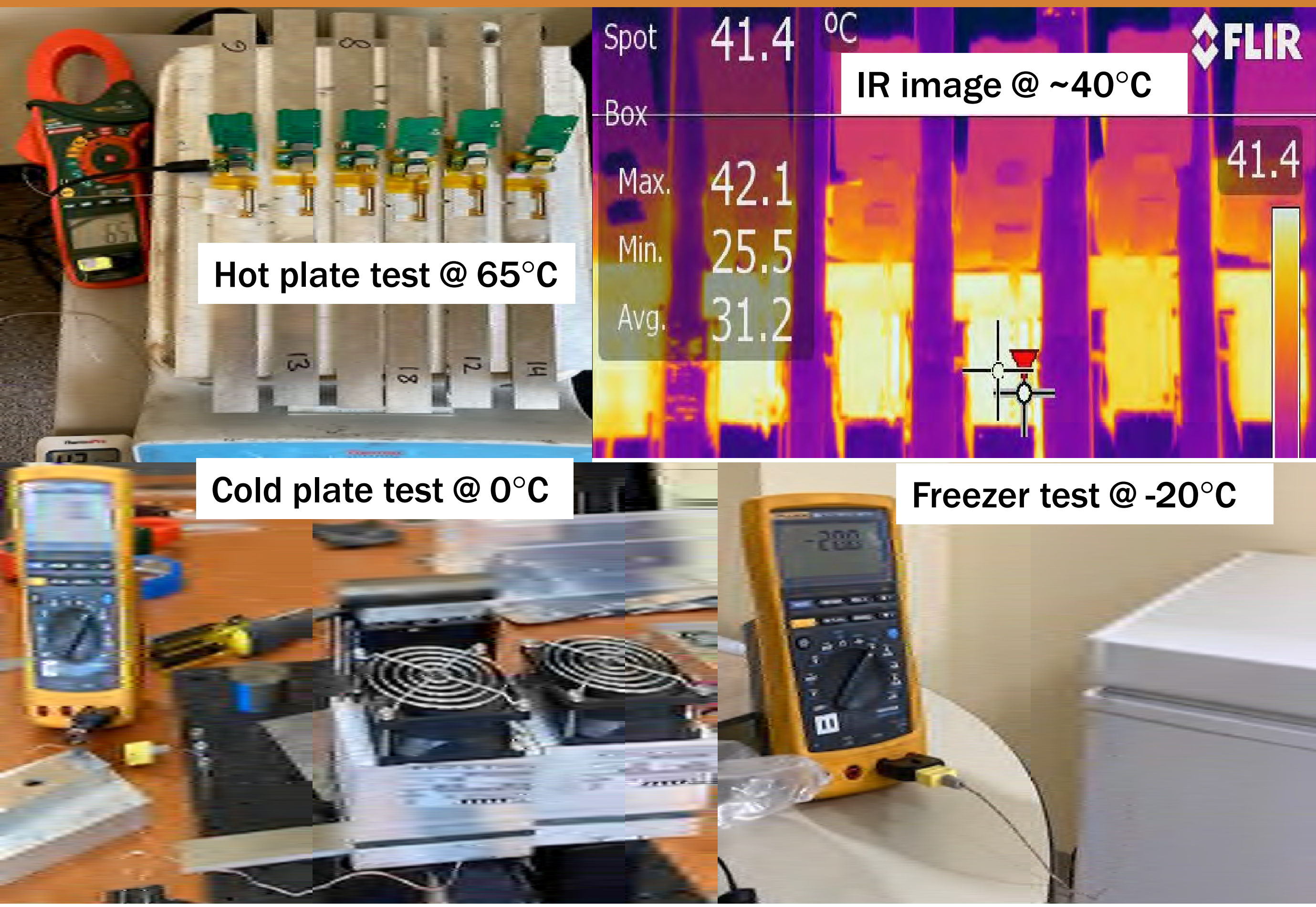
Self-Compensation Formulation

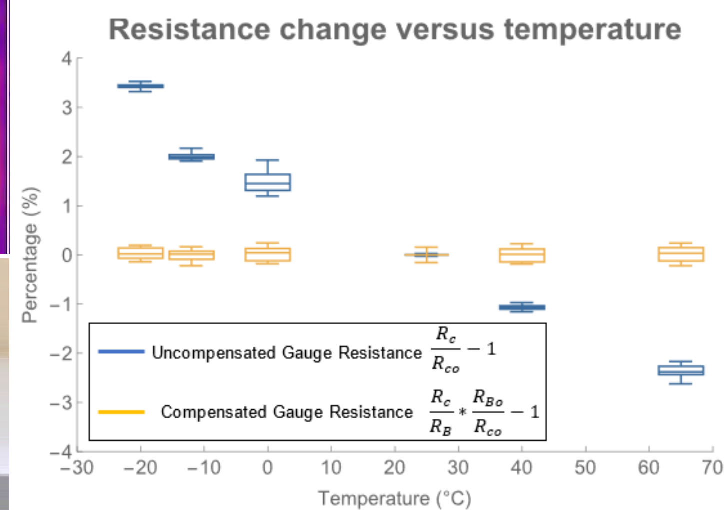
#	Components
1	M+A+N
3	M+A+C+D+Y
6	N+C+X
9	N+C+D+E+Z
10	X+D+Y
14	Y+E+Z

$$R = \frac{R_C}{R_D} * \frac{R_{Do}}{R_{co}} - 1$$

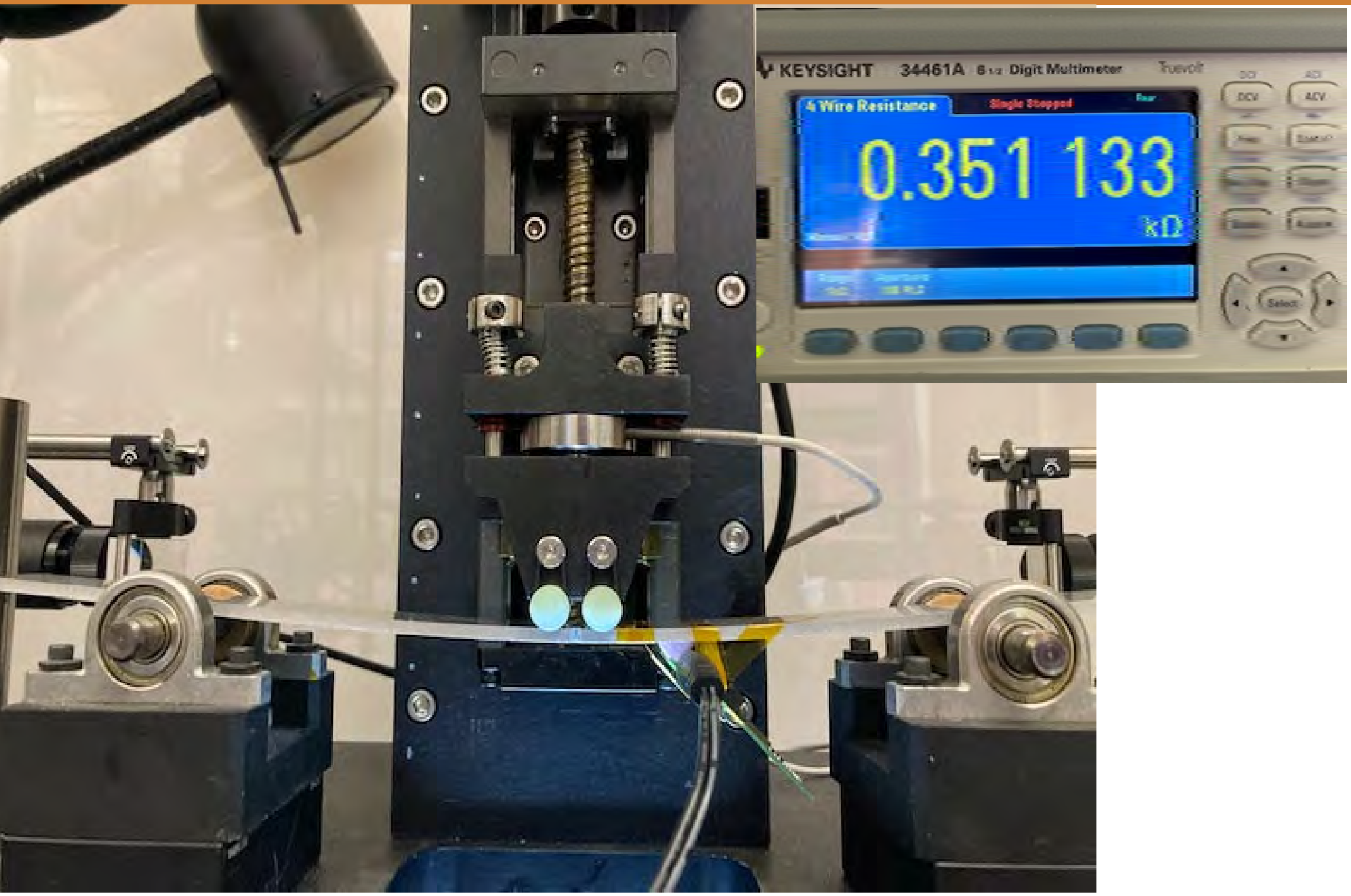
Zone	Formulation
2C	3+6-1-10
2D	9+10-14-6

DOE Temperature Test

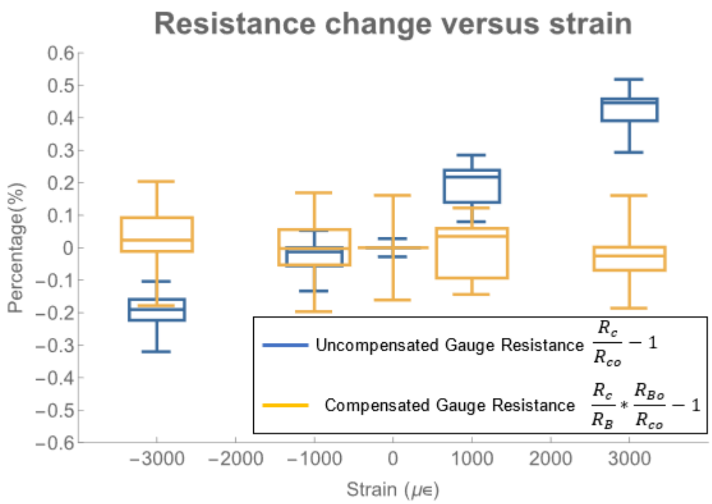




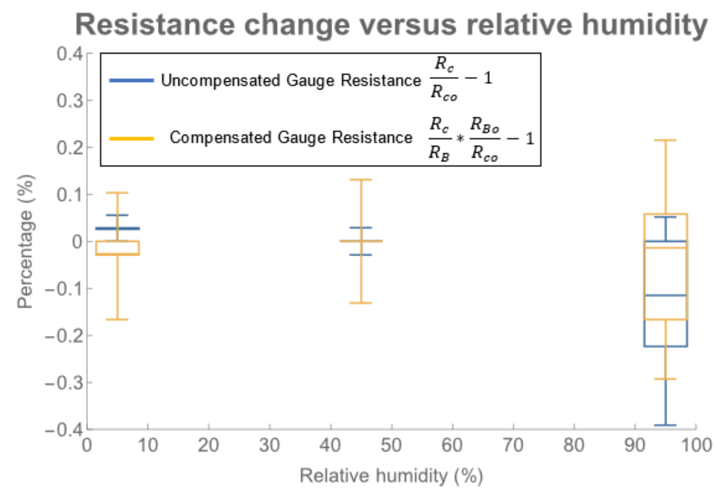
DOE Applied Static Strain Test



$$\varepsilon = \frac{value - 0.350376}{0.758447}$$

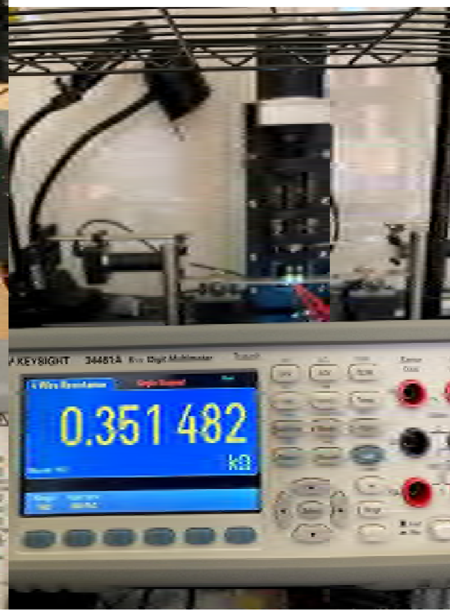


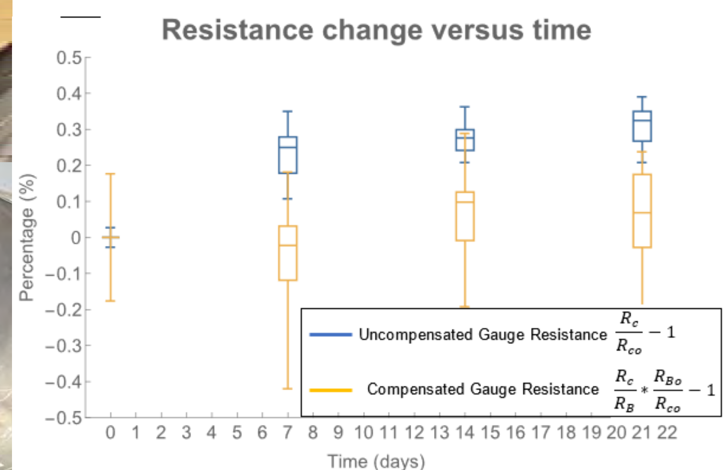
DOE Humidity Test



DOE Ageing Test

$$\varepsilon = \frac{value - 0.350376}{0.758447}$$





DOE Statistical Analysis

Coefficients:	Estimate	Std Error	t value	Pr(>|t|)
(Intercept)	1.95E-01	3.26E-03	59.802	< 2E-16
temperature	-2.79E-05	5.48E-05	-0.508	0.612
temp_time	1.71E-04	1.81E-04	0.947	0.345
strain	-1.17E-08	9.29E-07	-0.013	0.99
strain_time	1.76E-04	1.82E-04	0.968	0.334
strain_cycles	9.00E-09	1.00E-08	0.898	0.37
vacuum	6.38E-05	1.81E-04	0.353	0.725
RH	1.19E-05	6.12E-05	0.195	0.846
elapsed time	2.18E-05	1.32E-04	0.166	0.869

- Most variability in R is contained in sensor-to-sensor variability
  - ➢ Because system variability is low, indicates other variables are insignificant
  - ➢ Model fit shows no variable statistically significant for measurement of R

Examples of SEPOD Applied to SHM Methods

- SHM methods use for study
  - Potential Drop (PD) methods use change in resistance to indicate a <u>local</u> “hot spot” flaw
  - Guided Wave (GW) methods use piezoelectrics to detect <u>global</u> changes in ultrasonic wave propagation

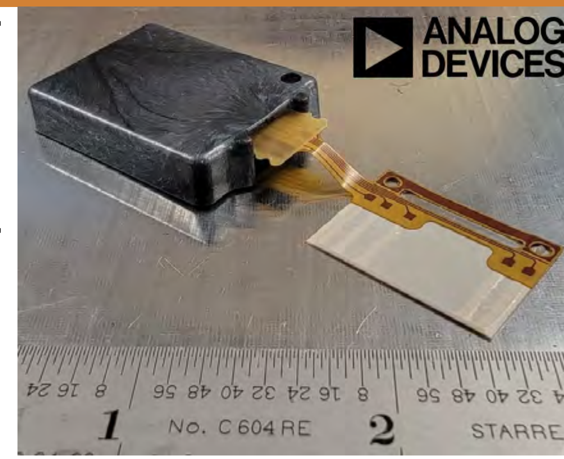
- Test methods used for study
  - 4-point bending of aluminum bar with EDM notch (fatigue crack growth for USAF)
  - Tensile-tensile fatigue of aluminum/lithium alloy bar with EDM notch (fatigue crack growth by FAA)

- Statistically Equivalent to POD (SEPOD) alternative models that capture data dependence
  - Length at Detection (LaD) developed by Dr. Floyd Spencer at Sandia National Laboratory
  - Random Effects Model (REM) developed by Prof. Meeker at Iowa State University

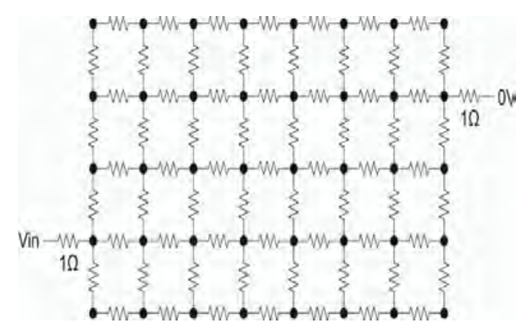
POD Example 1: Potential Drop (PD) Damage Detection (LOCAL)

- **Physical characteristics**
  - ➢ Form-factor: 1 x 1 cm (not a limitation)
  - ➢ Thickness: ~ 200 micron
  - ➢ Mass: ~10 mg/cm^2
  - ➢ Bend-radius: ~ 5 mm

Wireless Integrity Sensor Platform
WISP IoT Style Sensor
RF or inductive power
Bluetooth data transfer

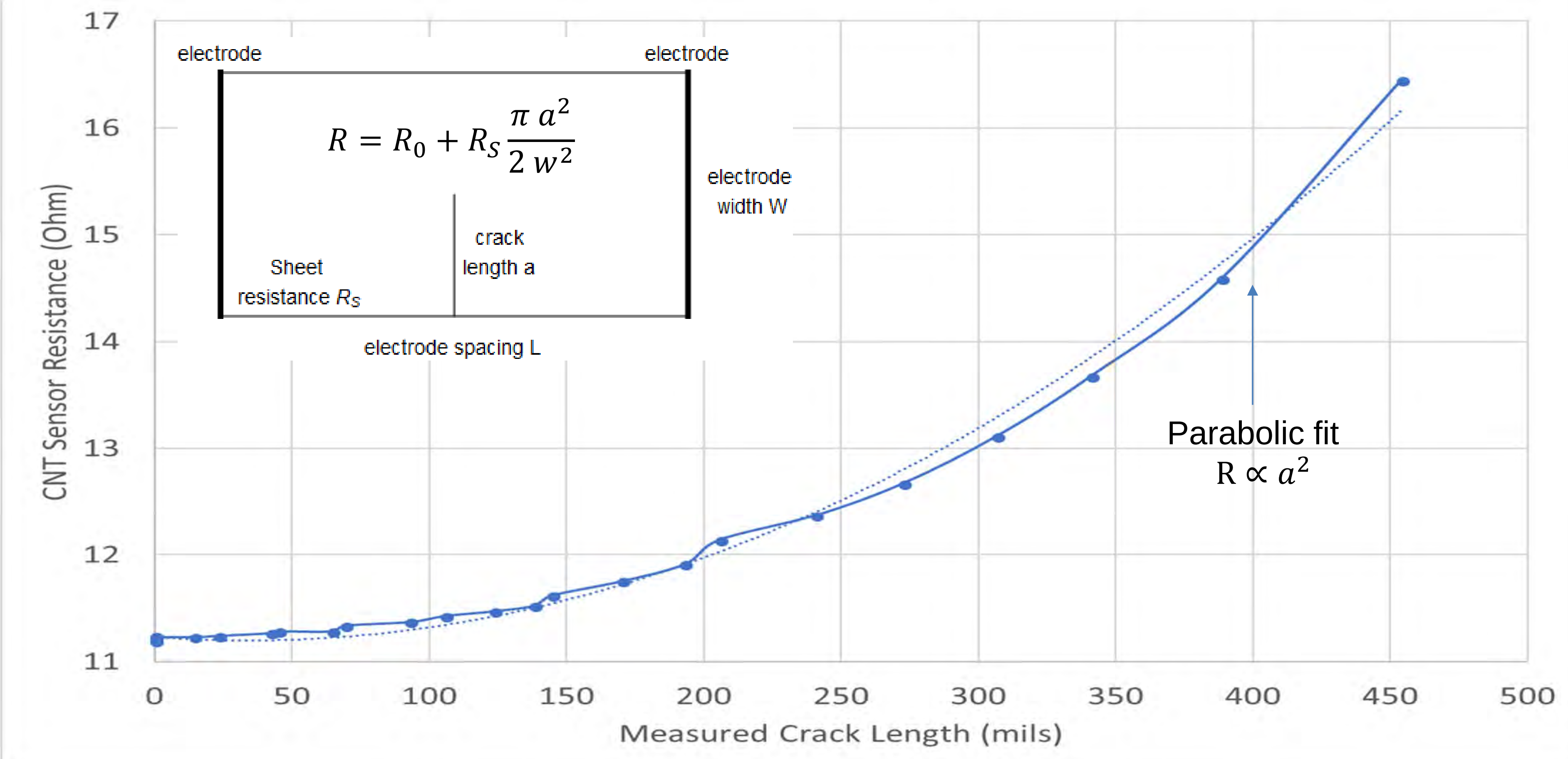


- **Crack detection mechanism**
  - ➢ Laminated CNT assembly bonds conformally to structure like strain gauge
  - ➢ CNT network electrical resistance changes proportional to crack length
  - ➢ Completely passive sensor, crack "recorded" even when no power applied

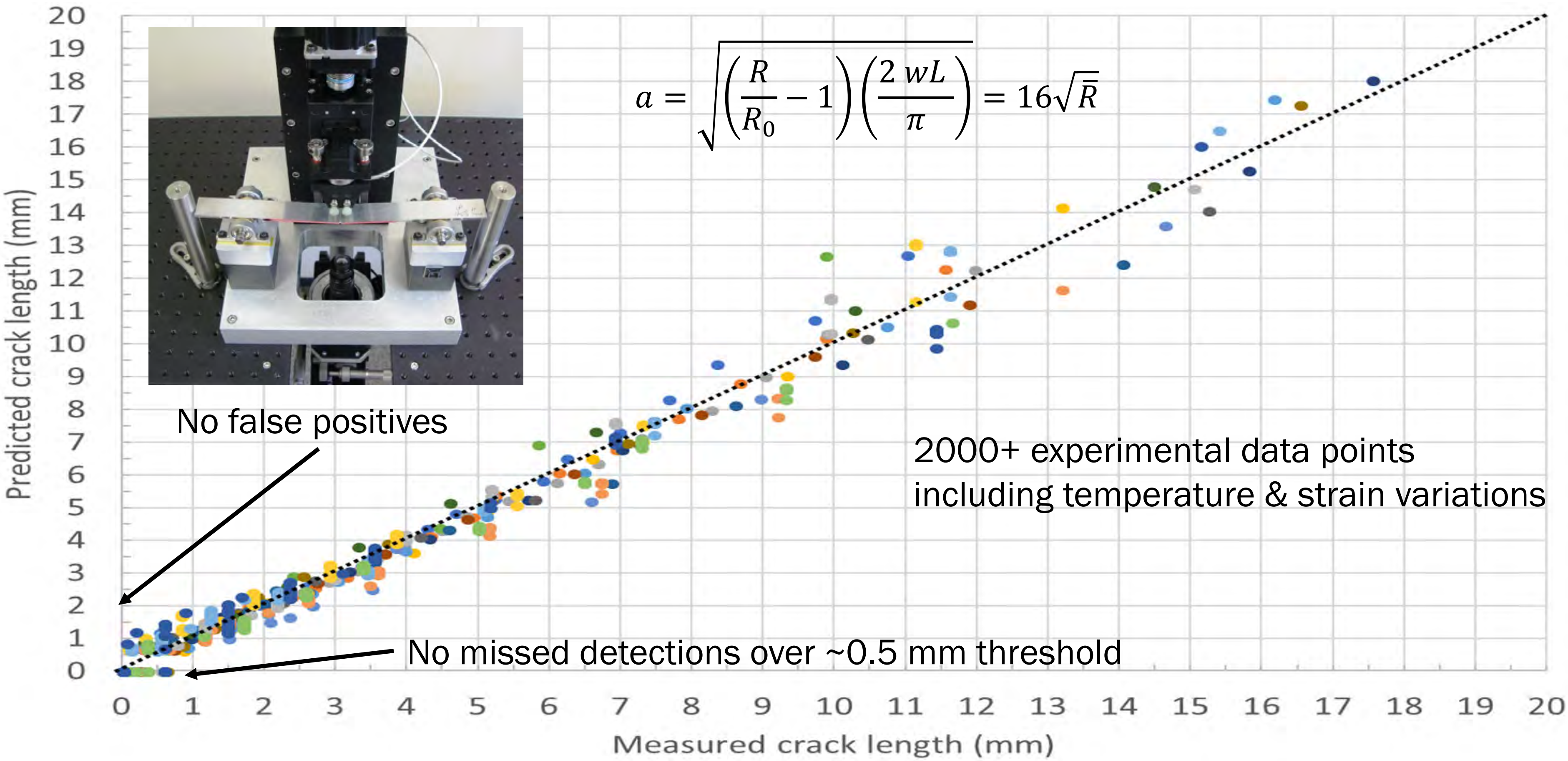


- **Benefits of CNT over conventional metallic foil crack gauges**
  - ➢ Continuous response (as opposed to fixed gated response)
  - ➢ More durable under static & fatigue loads, not susceptible to corrosion
  - ➢ Easy to fabricate in custom sizes and shapes, including cutouts

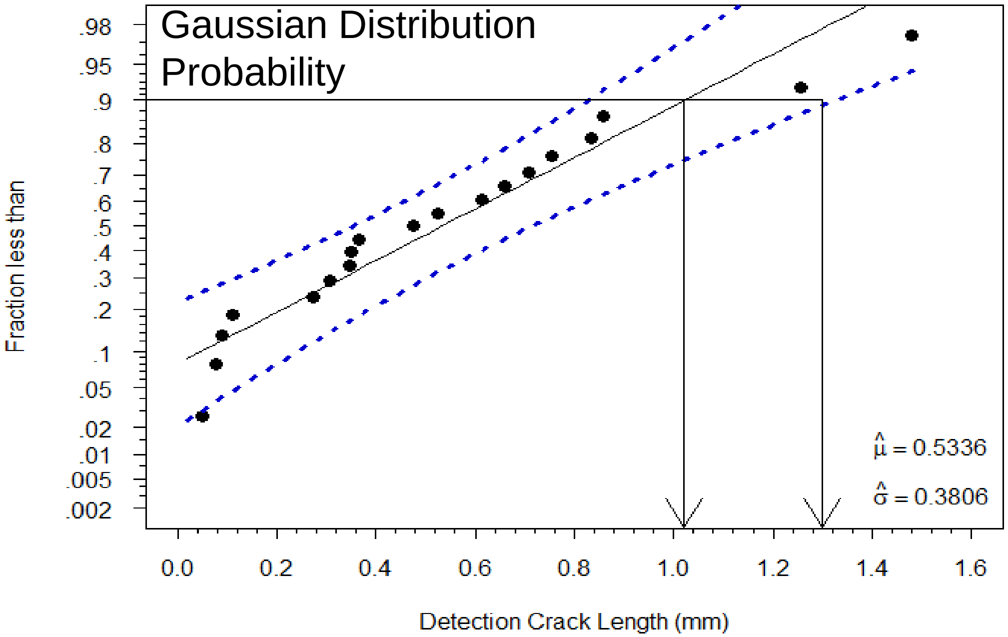
CNT Crack Gauge Resistance vs Measured Crack Length

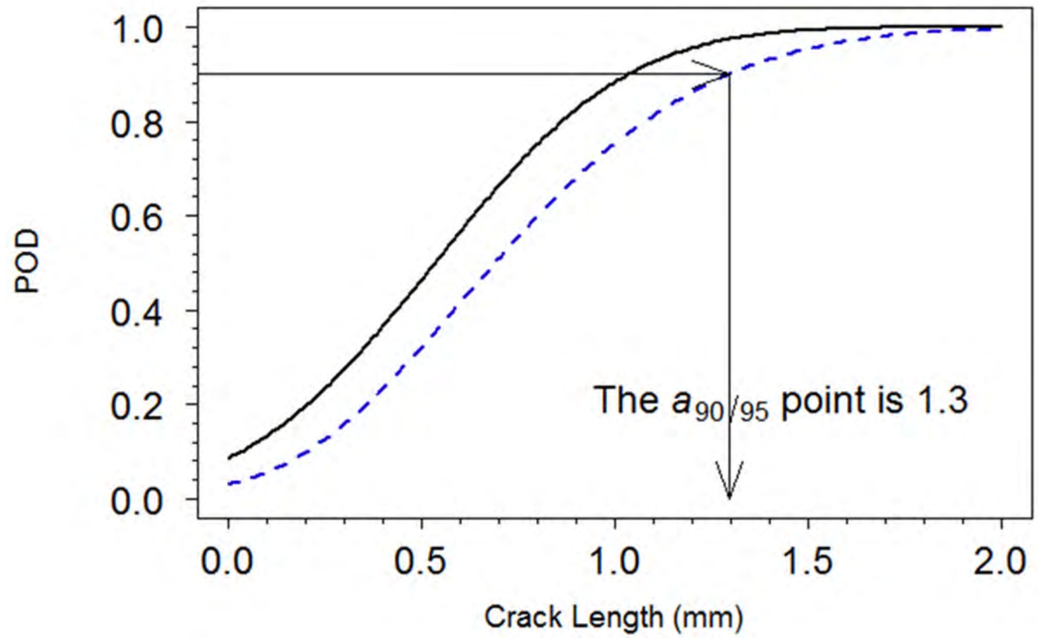


CNT Crack Gauge Predicted vs Measured Crack Length



PD Method Detection Sensitivity using Length at Detection Model

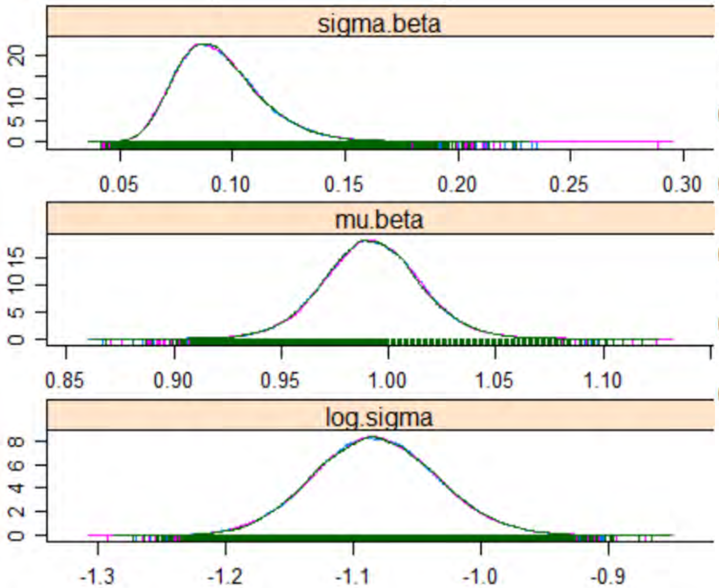




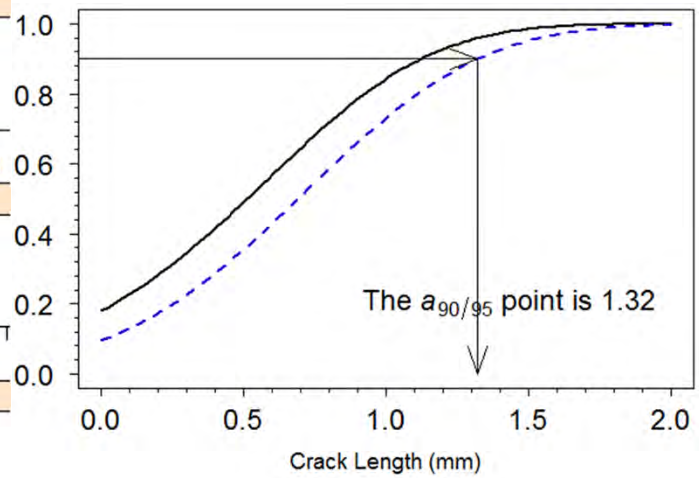
- **PD detection data is best fit by a gaussian distribution**
- **LaD provides an $a_{90/95}$ of 1.3 mm based on data *up until detection***
- **Statistical analysis performed by Prof. Bill Meeker at Iowa State University**

PD Method Detection Sensitivity using Random Effects Model

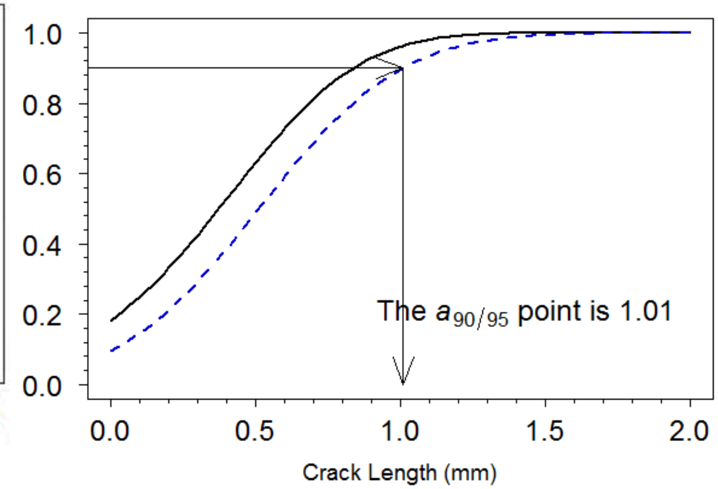
Bayesian Density Plots



POD – All Data

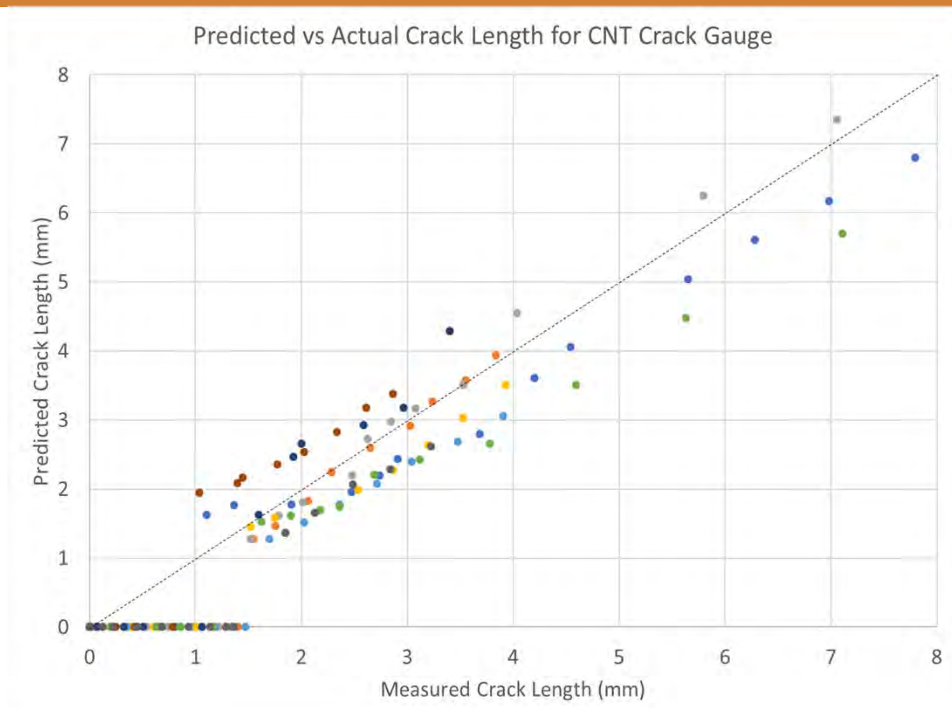


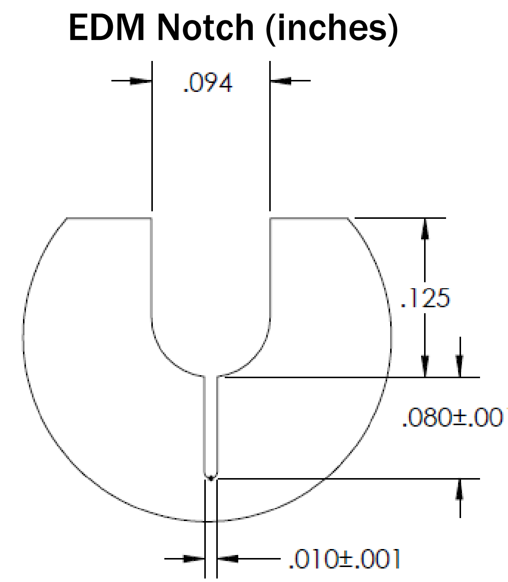
POD – Data < 5mm



- **Density Plots of Bayesian Estimation Results**
- **REM provides an $a_{90/95}$ of 1.32 mm using all data (up to 18 mm)**
- **$a_{90/95}$ improves to 1.01 mm when only considering data < 5 mm**

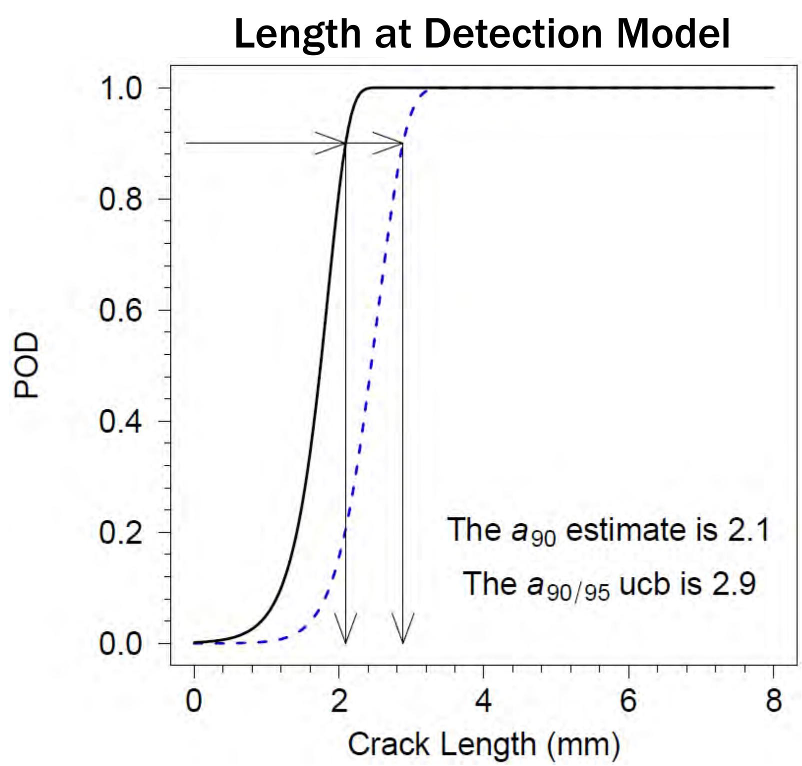
PD Method Blind Detection Sensitivity Evaluation at FAA Tech Center

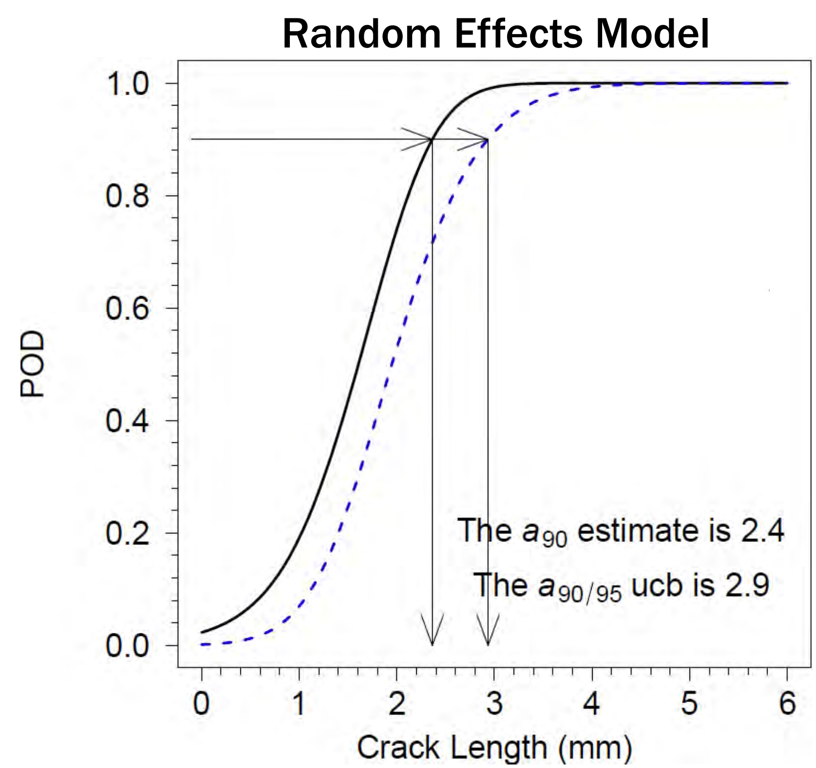




- Additional blind testing conducted through FAA Tech Center in Atlantic City
- Tensile-tensile fatigue tests on 9 Al-Li bars with EDM notch (data every 1000 cycles)
- Prediction + visual crack data sent to Prof. Meeker @ ISU for SEPOD analysis

PD Method Blind Detection Sensitivity Study Results from FAA





- **SEPOD models used to estimate $a_{90/95}$ from blind data, same parameters as prior test**
- **$a_{90/95}$ slightly higher than lab results, fatigue-driven heating suspected (uncompensated)**

Comparison of Potential SEPOD Approaches

- Length-at-Detection (LaD) method
  - Computationally simple
  - Requires a minimal amount of data (just until first detection)
  - Requires assumption about distribution of detectable crack sizes (e.g., normal or lognormal), with little information to discriminate among different assumptions that might give vastly different $a_{90/95}$ values
  - $a_{90/95}$ of 1.3 mm calculated for 4-pt fatigue, 2.9 mm for tensile fatigue

- Random Effects Model (REM) method
  - Uses available data more efficiently
  - More information to check model assumptions
  - More robust to departures from model assumptions
  - Provides a framework for model-assisted probability of detection (MAPOD)
  - More complicated computational algorithms are needed
  - $a_{90/95}$ of 1.3 mm calculated for 4-pt fatigue, 2.9 mm for tensile fatigue

POD Example 2: Guided Wave (GW) Damage Detection (GLOBAL)

- GW uses ultrasonic excitation of structure to produce Lamb waves
  - Measure transmission/ reflection of wave energy's interaction w/structure
  - Piezoceramic (PZT) wafers commonly used as actuators & sensors
  - PZT expand/contract w/high force-potential when dynamic voltage applied
  - Can operate at high frequencies (10 kHz - 10 MHz), good for actuation
  - Dynamic strain creates potential between electrodes, good for sensing

- PZT beamforming array (structural sonar) was used for presented work
  - Central 6 mm ∅ actuator surrounded by six 3 mm ∅ sensors (spaced 60°)
  - Narrowband linear 50 - 250 kHz sinusoidal chirp excitation at 20Vpp

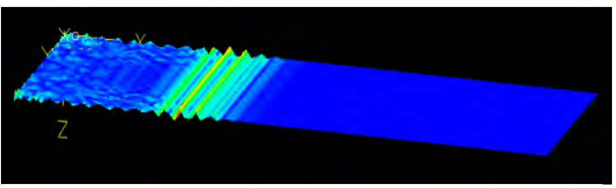
Raytheon Technologies

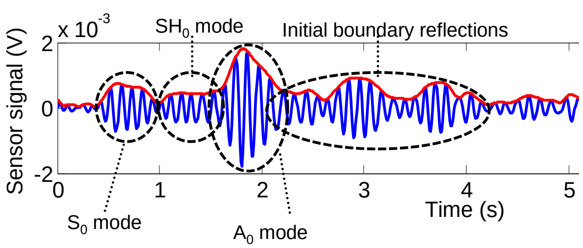
15 mm

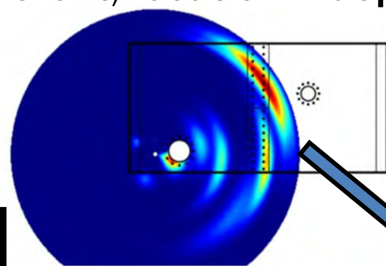
MD7-Pro Distributed Data Acquisition Hardware

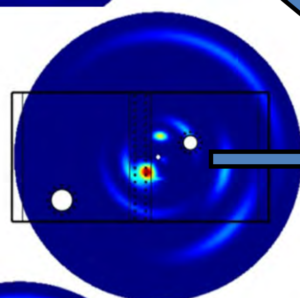
GW Method Beamforming PZT Array for Damage Detection

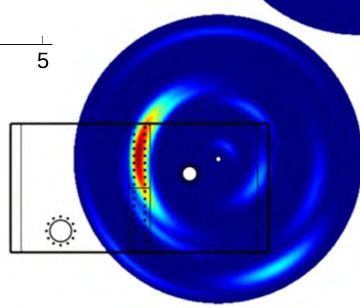
Each node processes phase-coherent, location independent "sonar-scan"



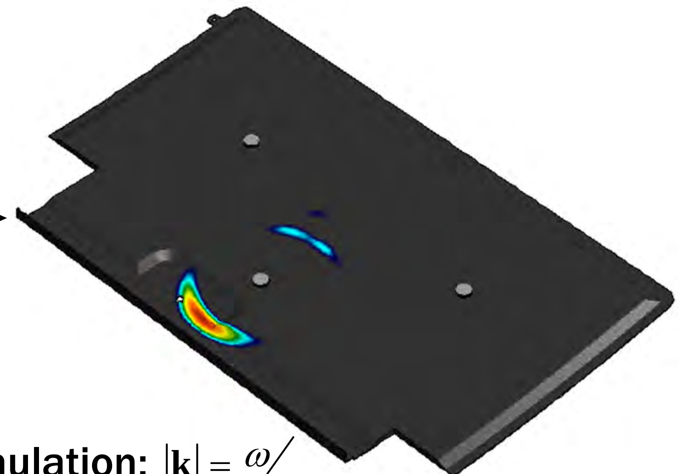








Sum scans incoherently to form composite image



Damage Index (DI) Formulation: $|\mathbf{k}| = \omega / c_p$

$$\mathbf{B}(\mathbf{k}') = \sum_{m=0}^{M-1} \exp\left(j\left(\mathbf{k}'^{\mathrm{T}} - \mathbf{k}^{\mathrm{T}}\right)\mathbf{p}_m\right) \tilde{y}(t) \exp\left(j\omega t\right)$$

$\mathbf{k}$ wavenumber
ω temporal frequency
c_p A_0 phase velocity

Color represents # of standard deviations above mean of damage-free data

GW Method Detection Sensitivity Assessment Experiments

- 4-point bend fixture used again
  - 8 aluminum beams tested (300 x 25 x 3 mm)
  - 50,000 fatigue cycles at room temperature
  - PZT arrays bonded to either end of beam
- FAA tensile-tensile fatigue specimens shared
  - 9 Al-Li specimens tested (600 x 40 x 2 mm)
  - 35,000 fatigue cycles at room temperature
  - PZT arrays bonded 90 & 115 mm from EDM notch
- Statistical analysis performed by Prof. Meeker
  - Data collected every 1,000 cycles in both cases
  - One specimen used for crack length calibration
  - LaD analysis performed, too much scatter for REM

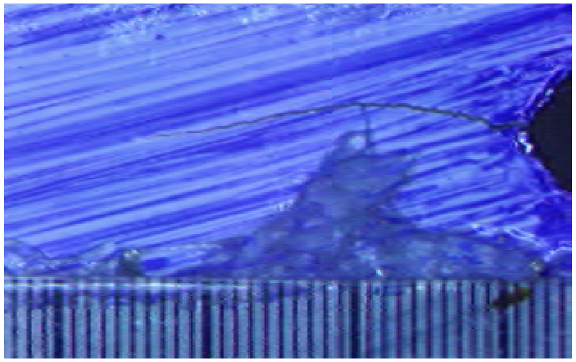
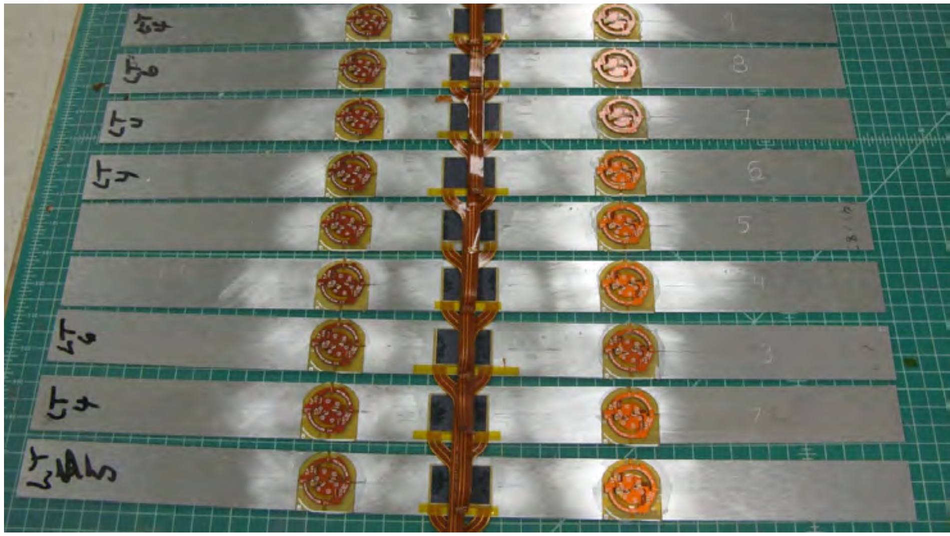
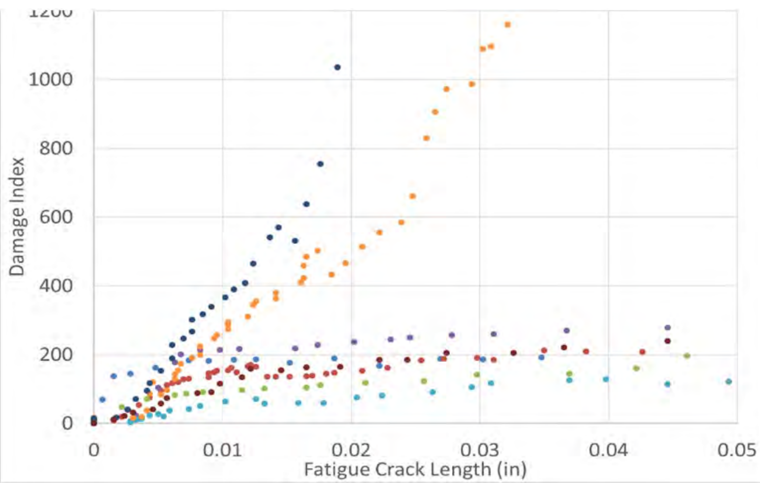


Image of Crack from EMD Notch

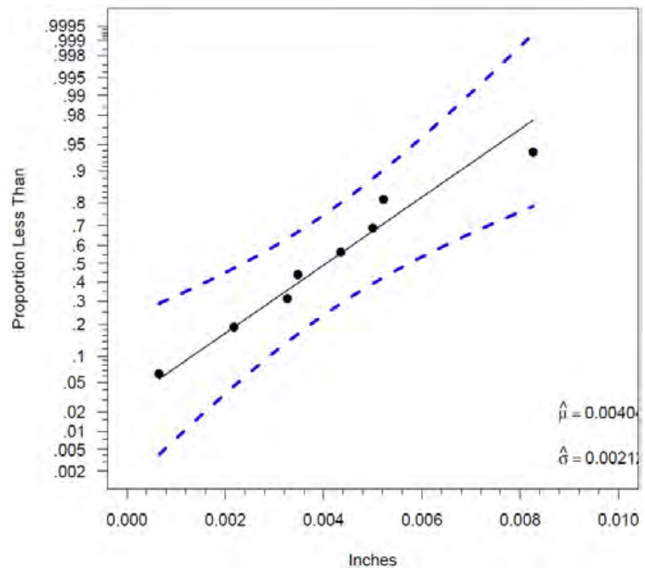


GW Method Detection Sensitivity using LaD Model (4-Point Bending)

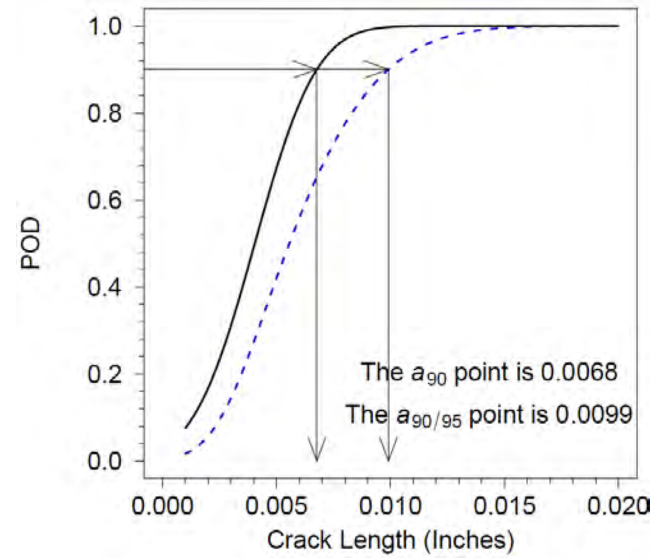
Pitch-Catch Energy Metric vs Crack Length



Gaussian Probability Plot



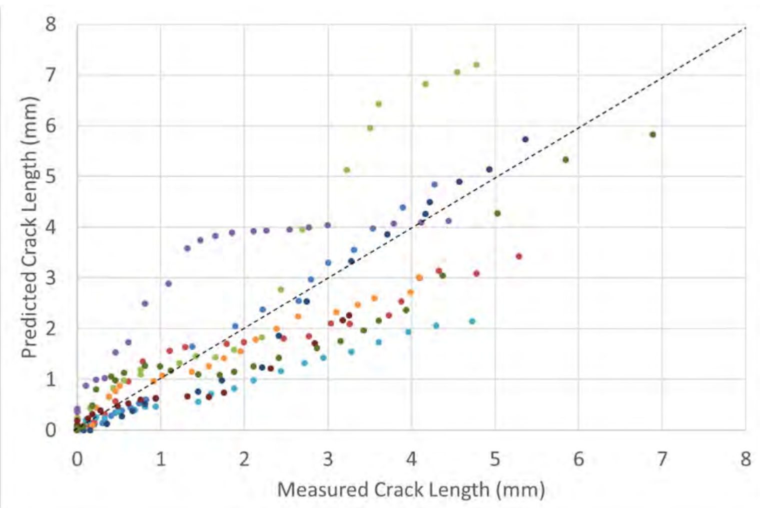
Sensitivity using LaD



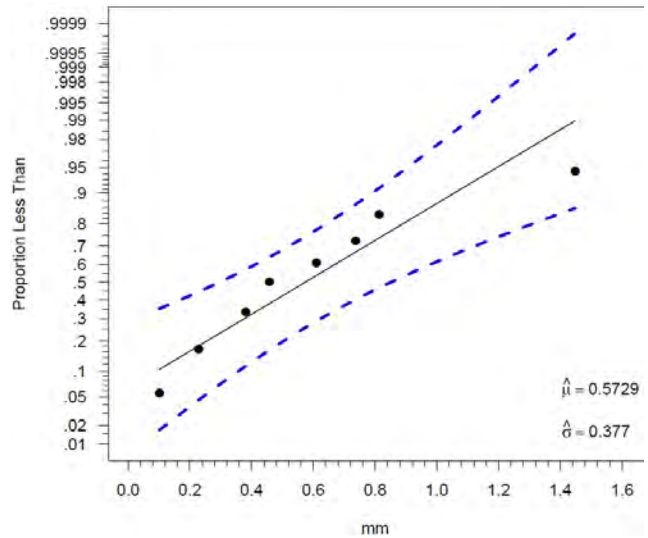
- **GW detection data is best fit by a Gaussian distribution**
- **LaD provides an $a_{90/95}$ of 0.25 mm based on data *up until detection***
- **Did observe odd phenomenon after detection w/DI's following 2 diverging trends**

GW Method Pitch-Catch Detection Sensitivity using LaD Model (FAA)

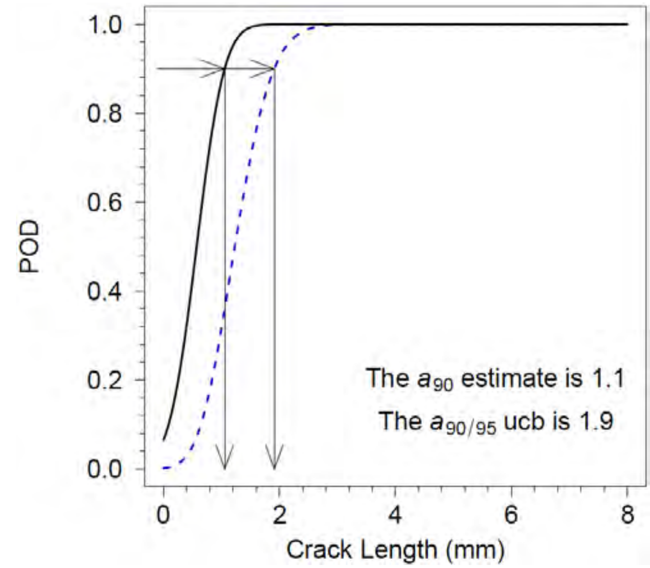
Predicted vs Measured Crack Length



Gaussian Probability Plot



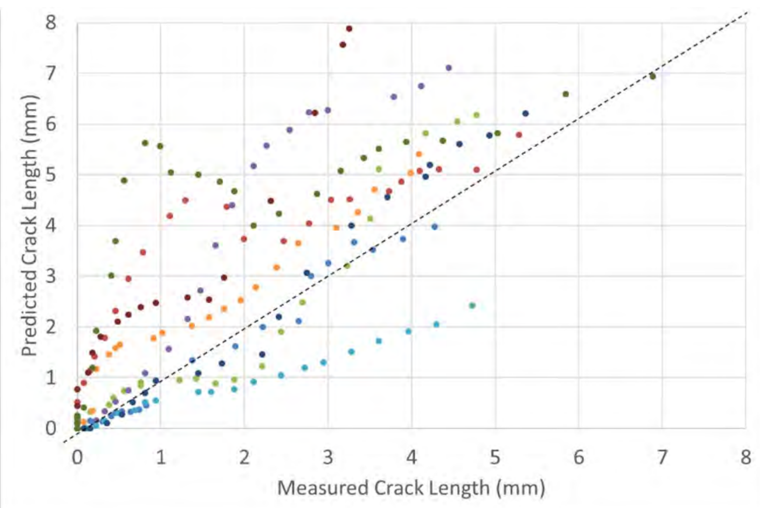
Sensitivity using LaD



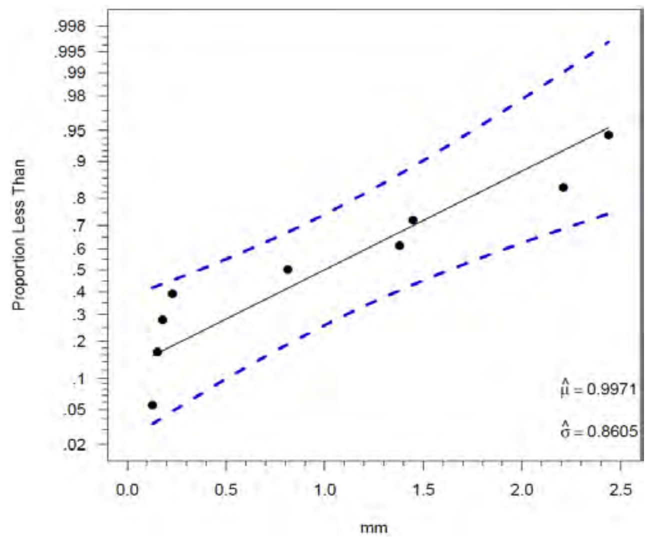
- Pitch-Catch (PC) data using PZT pairs on either side of EDM notch
- Able to produce better accuracy with additional sensor paths
- Analysis of PC data yields an $a_{90/95}$ value of 1.9 mm

GW Method Pulse-Echo Detection Sensitivity using LaD Model (FAA)

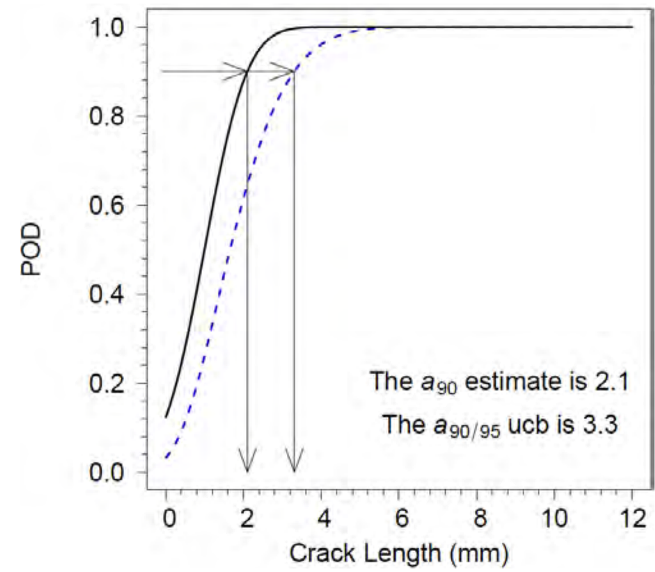
Predicted vs Measured Crack Length



Gaussian Probability Plot



Sensitivity using LaD



- Pulse-Echo (PE) data using PZT data from sensors independently
- Advantage of only using one sensor array, better at boundaries
- Analysis of PE data yields an $a_{90/95}$ value of 3.3 mm

metis design

Summary of Preliminary SEPOD Assessment

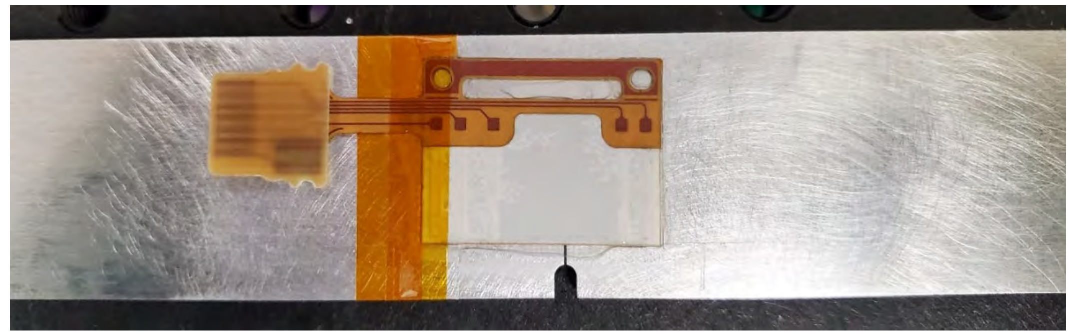
- Investigation of alternative detection sensitivity models applied to PD & GW SHM method
  - 4-pt bending fatigue of Al beams
  - Tensile-tensile fatigue of Al/Li beams
  - Prof. Meeker (Iowa State) for statistical analysis
  - 2 statistical approaches: Length at Detection (LaD) & Repeated Measured Model (REM)

- Initial detection sensitivity results for PD method
  - Results have been consistent between LaD & REM^2 approaches
  - $a_{90/95}$ value of 1.3 mm for laboratory 4-pt bending fatigue
  - $a_{90/95}$ value of 2.9 mm for blind tensile-tensile fatigue (temp variations)

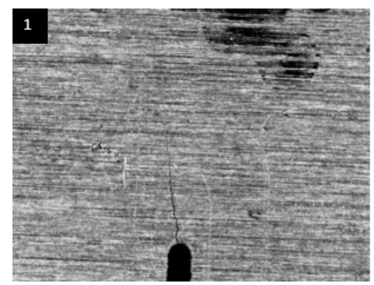
- Initial detection sensitivity results for GW method
  - $a_{90/95}$ value of <1 mm for laboratory 4-pt bending fatigue
  - $a_{90/95}$ value of 1.9 mm for pitch-catch (PC) data in blind tensile-tensile fatigue
  - $a_{90/95}$ value of 3.3 mm for pulse-echo (PE) data in blind tensile-tensile fatigue

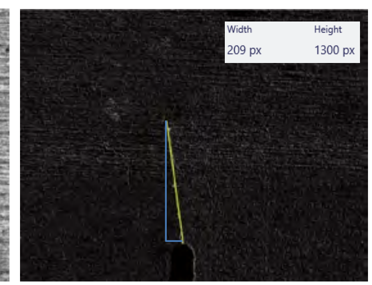
- **Need much more data to *validate* alternative SEPOD approaches vs MIL-HDBK-1823A**

Detection Sensitivity Validation Study



- Next step is to evaluate detection sensitivity using a large dataset (100 specimens)
  - ➢ 4-pt bending with EDM notch on tensile side
  - ➢ 1000 $\mu\varepsilon$ with R ratio of 0.1
  - ➢ Truth data collected via digital image correlation (DIC)
  - ➢ WISP data collected every 100 cycles (loaded & unloaded states)





- POD evaluation performed by 3 consulting statisticians
  - ➢ Will perform traditional MIL-HDBK-1823A POD analysis using single datapoint from each specimen
  - ➢ Will also use new models to evaluate POD with subsets of fewer specimens but more datapoints
  - ➢ Will investigate use of MAPOD for extending the applicability of SEPOD results (CIVA & analytical code)

Real-Life Applications of MD7-Pro & WISP SHM Systems

Lessons Learned

- Installation conditions
  - 50%+ our installations require a lift/scaffold (limited ability to access tools & power)
  - 90%+ have been on vertical surfaces or overhead (as opposed to flat horizontal work area)
  - Structures are rarely flat, must consider convex & concave curvature, weld lines, fasteners, etc
  - Some locations may have sufficient room for sensors, but not for hands and/or installation tools
  - Nearly impossible to apply pressure/vacuum for most applications
  - Temperature control is challenging (limited ability to use heating lamps or blankets)
  - Temporary fixtures may stick too well to primed metal, not at all to treated composite structures
- Connectors & cables
  - 100% of our applications have spent more time/budget on connectors/cables than sensors/hardware
  - Very strict requirements on ALL cable materials, multiple aerospace/MIL standards, even pins used
  - Every application will have standards on bend radius, tie down requirements (have seen every 6”)
- Electrical emission (both radiated & conducted) is very challenging and a bit of an art
  - Consider very early on or you may need to re-design & certify all your sensors/hardware/cables

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