Taking your NDT System Along for the Ride

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structural health monitoring
multi-functional materials
lean enterprise solutions

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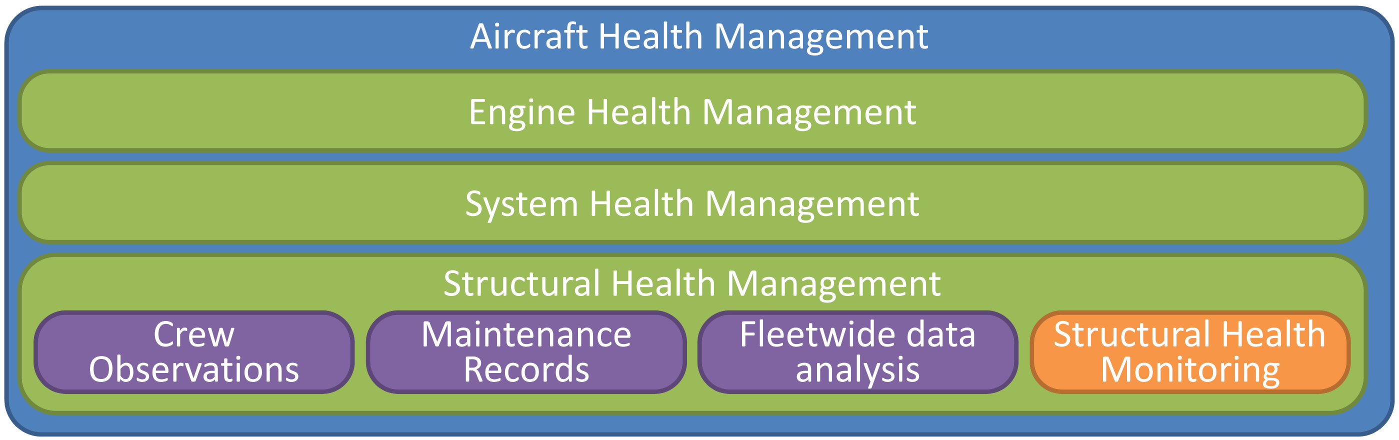
What is SHM?

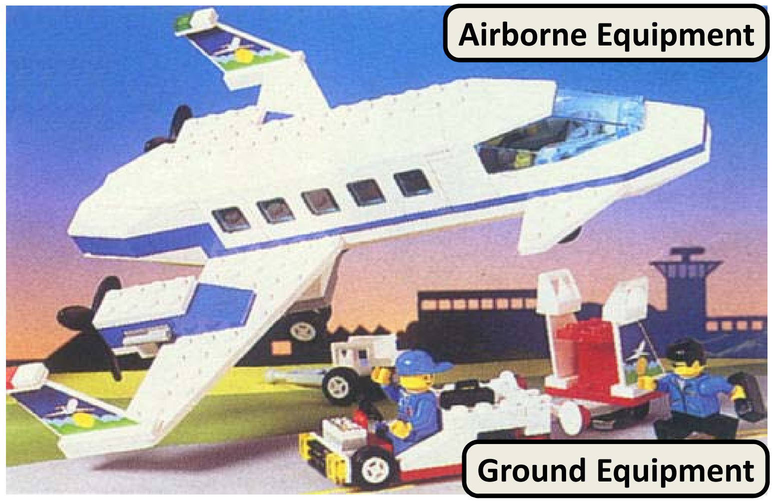
- **Structural Health Monitoring (SHM)**
  - ➢ **Defined by Aerospace Industry Steering Committee for SHM (AISC-SHM) in ARP-6461 (also A4A MSG-3)**
    - — **"the process of acquiring & analyzing data from on-board sensors to evaluate the health of a structure"**
  - ➢ **Defined by United States Air Force (USAF) in MIL-STD-1530D**
    - — **"a nondestructive inspection process or technique that uses in-situ sensing devices to detect damage"**
  - ➢ **Essentially a suite of NDT sensors that fly ATTACHED TO the aircraft**
    - — **could include any presently installed aircraft sensors and/or application-specific new sensors to be installed**



SHM Architecture

OPERATIONAL MONITORING

- Fatigue Monitoring
- Incident Monitoring
- Environmental Monitoring



DAMAGE MONITORING

- Fatigue damage sensing
- Environmental damage sensing
- Accidental damage sensing

OUTPUTS

- Usage Evaluation
- Advisory Indication
- Inspection Result

BENEFITS

- Improve Repair Planning
- Increase Inspection Intervals
- Reduce Inspection Time and Cost

Direct Maintenance Cost

- Reduce Weight, Cost & Downtime

Direct Operating Cost

- Increase Residual Value
- Life Extension

Ownership Cost

How does SHM Differ from NDT?

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

- 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, complex geometry & depth limitations
  - Eliminate costly & potentially detrimental disassembly (collateral damage)

What are the Consequences of these Differences?

- Still requires same detection sensitivity quantification as traditional NDT
  - Probability of Detection (POD) & Probability of False Positive (PFP)
  - 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 design of experiment (DOE)

- Now must also qualify airworthiness similar to any airborne hardware
  - Environmental (range of typical operating conditions does not effect performance)
  - Mechanical (will not become a projectile under shock/impact/vibration loading)
  - Electrical (will not interference with other on-board equipment)
  - Software* (special considerations if system is powered in flight vs just ground-based collection)

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

Probability of Detection Quantification not as Straightforward

- MIL-HDBK-1823A most common precedent to assess sensor detection capabilities
  - Key metric is $a_{90/95}$ - 90% probability of detection (POD) with 95% confidence
  - Must keep probability of false positive low too (i.e. minimize incorrect indications)

- 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)
  - Statistically Equivalent to POD (SEPOD) alternative models for SHM that capture degree of 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

- Examples of SHM methods
  - Potential Drop (PD) methods use change in resistance to indicate a local "hot spot" flaw
  - Guided Wave (GW) methods use piezoelectrics to detect global changes in ultrasonic wave propagation

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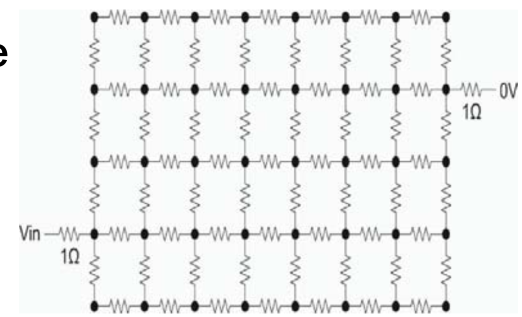
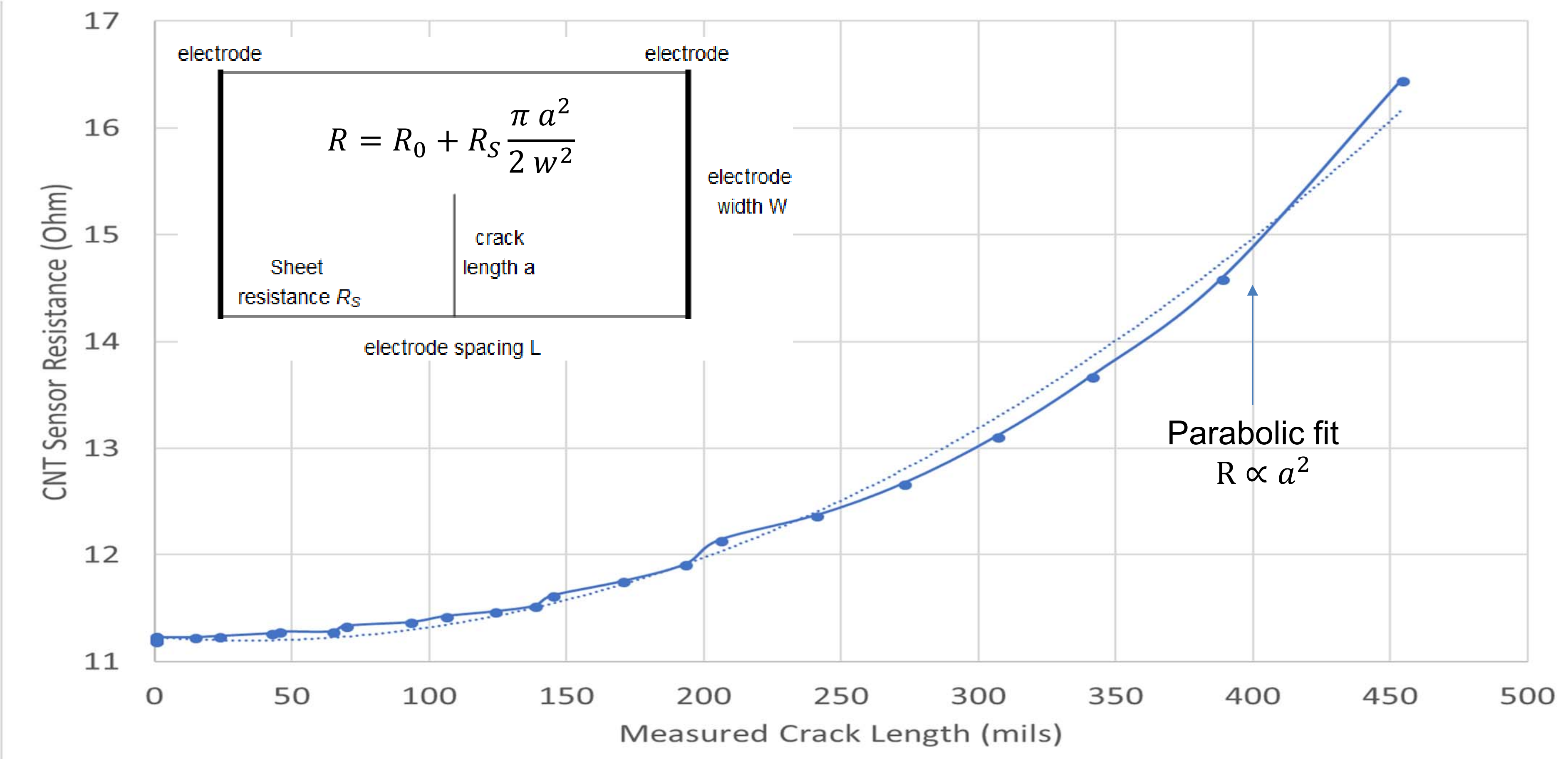
Example Case 1: Potential Drop (PD) Damage Detection (LOCAL)

- Physical characteristics
  - Form-factor: 2 x 2 cm (can be anything)
  - Thickness: ~ 100 micron
  - Mass: ~10 mg/cm^2
  - Bend-radius: ~ 5 mm

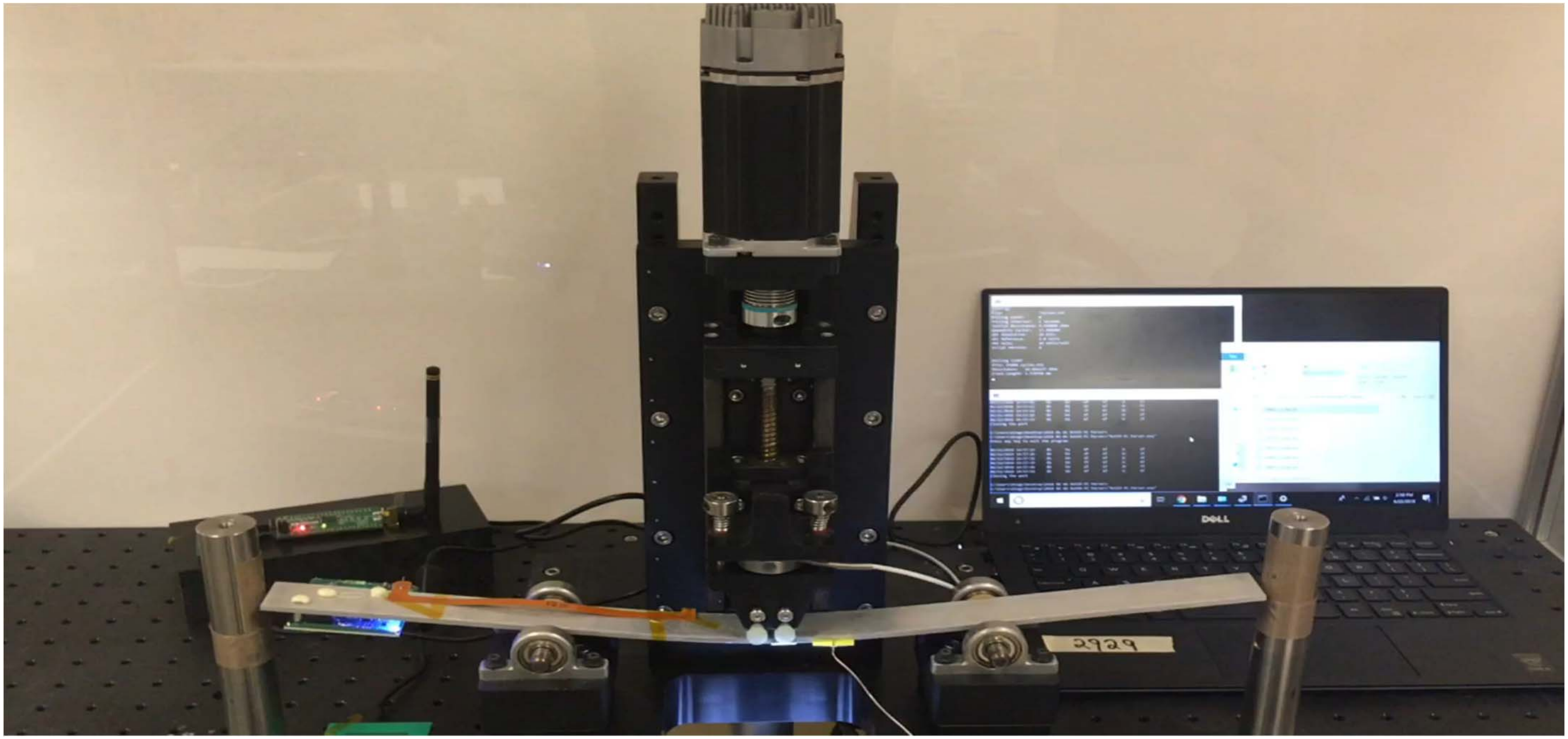


- Crack detection mechanism
  - Laminated CNT assembly bonds conformally to structure like strain gauge
  - CNT network electrical resistance changes proportional to crack length
  - Completely passive sensor, crack "recorded" even when no power applied
- Benefits of CNT over conventional metallic foil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

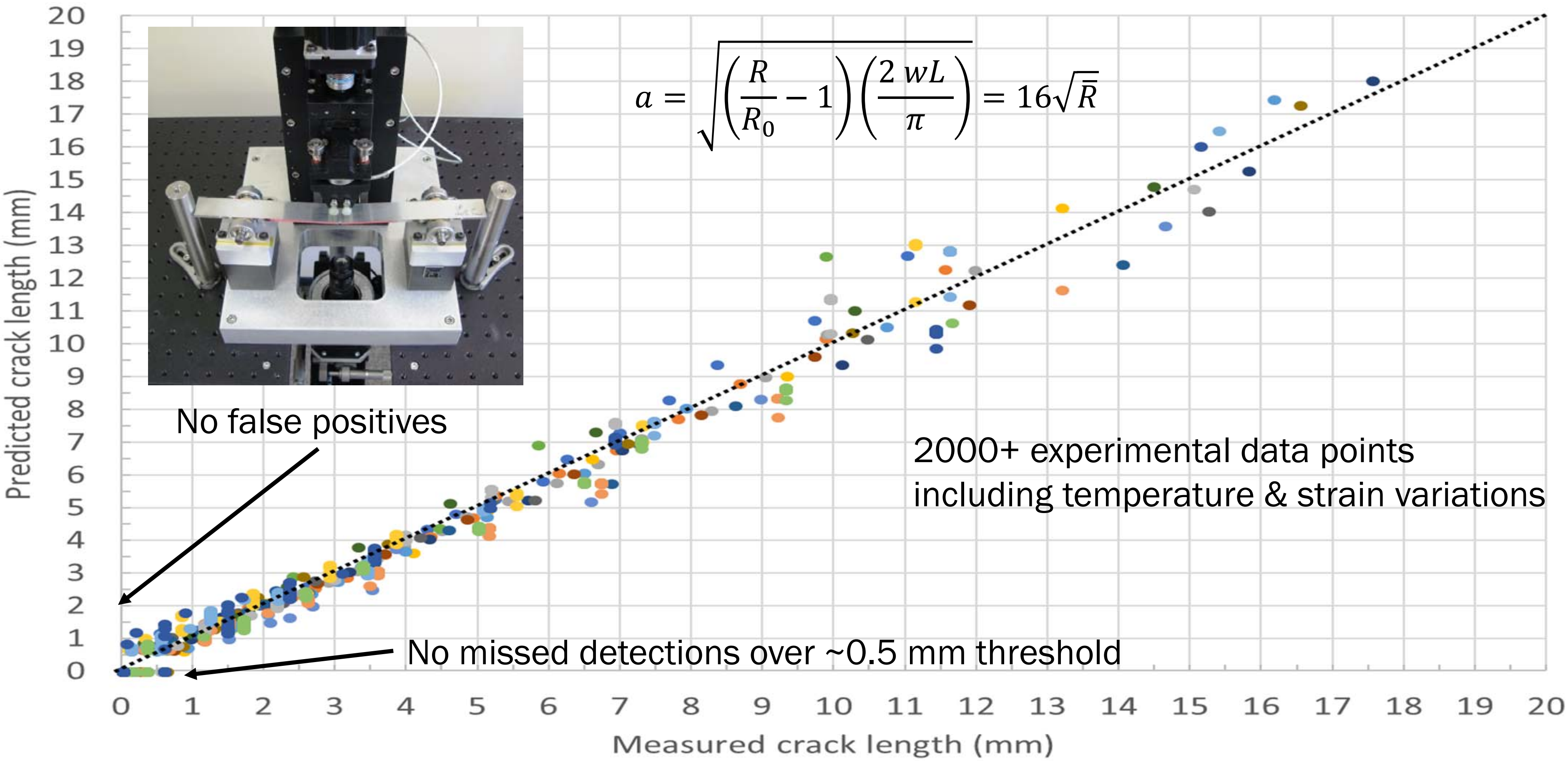
CNT Crack Gauge Resistance vs Measured Crack Length



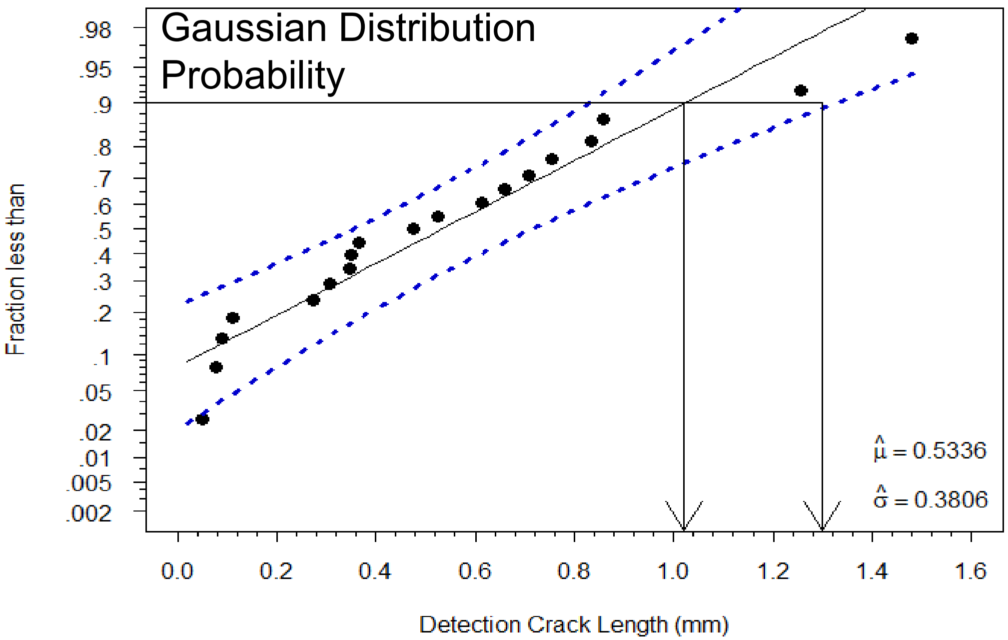
Hyperlapse Video of 4-Point Bending Fatigue in Action @ 3300 $\mu\varepsilon$

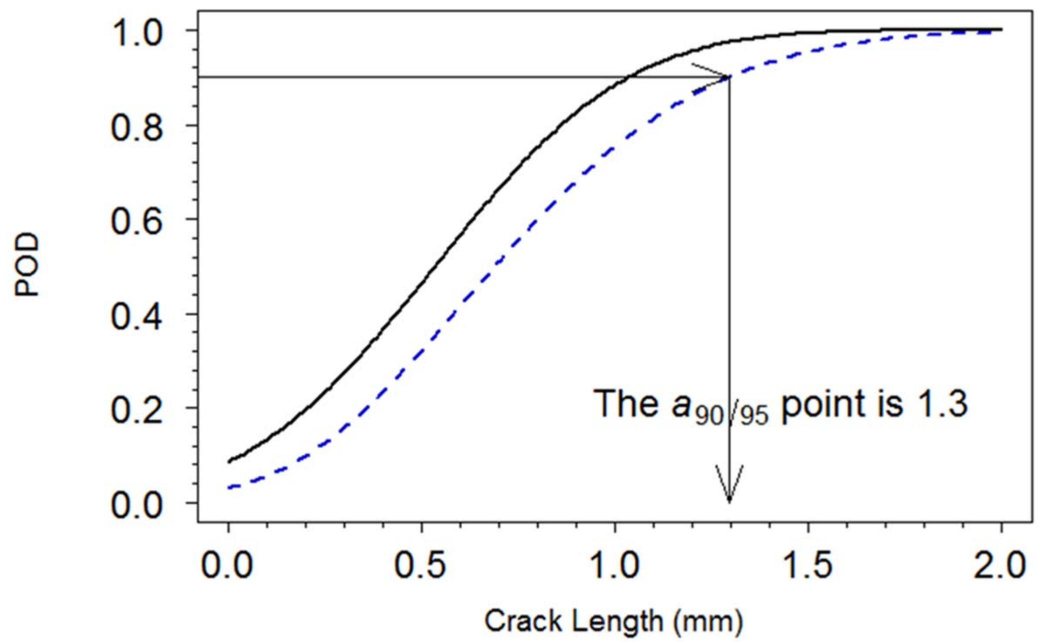


CNT Crack Gauge Predicted vs Measured Crack Length



PD Method Detection Sensitivity using Length at Detection Model

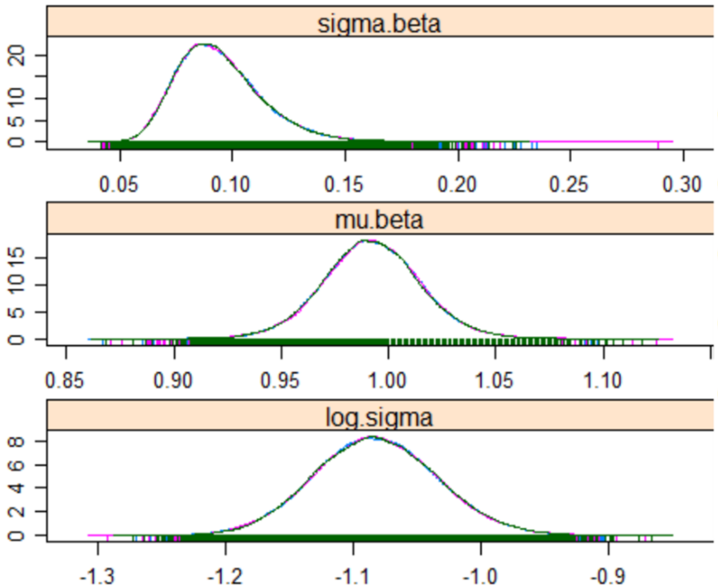




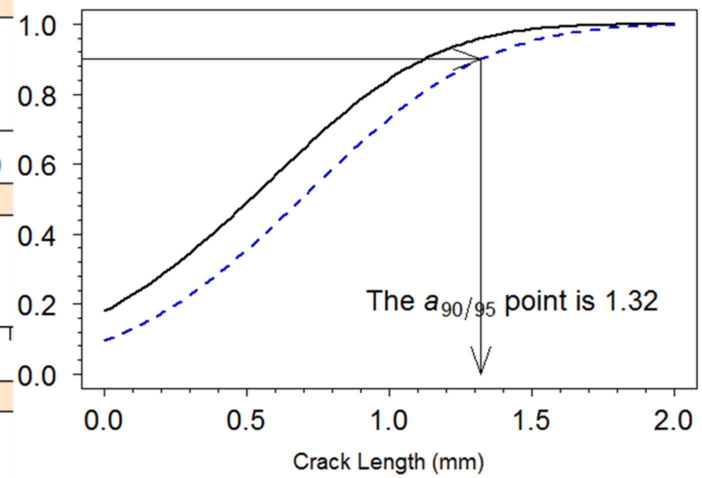
- **PD detection data is best fit by a gaussian distribution**
- **LaD provides an $a_{90/95}$ of 1.3 mm based on data *up until detection***
- **Statistical analysis performed by Prof. Meeker @ ISU as consultant**

PD Method Detection Sensitivity using Random Effects Model

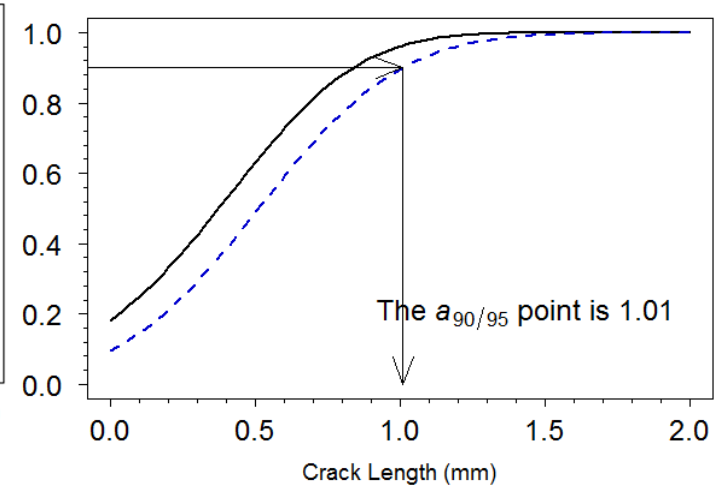
Bayesian Density Plots



POD – All Data

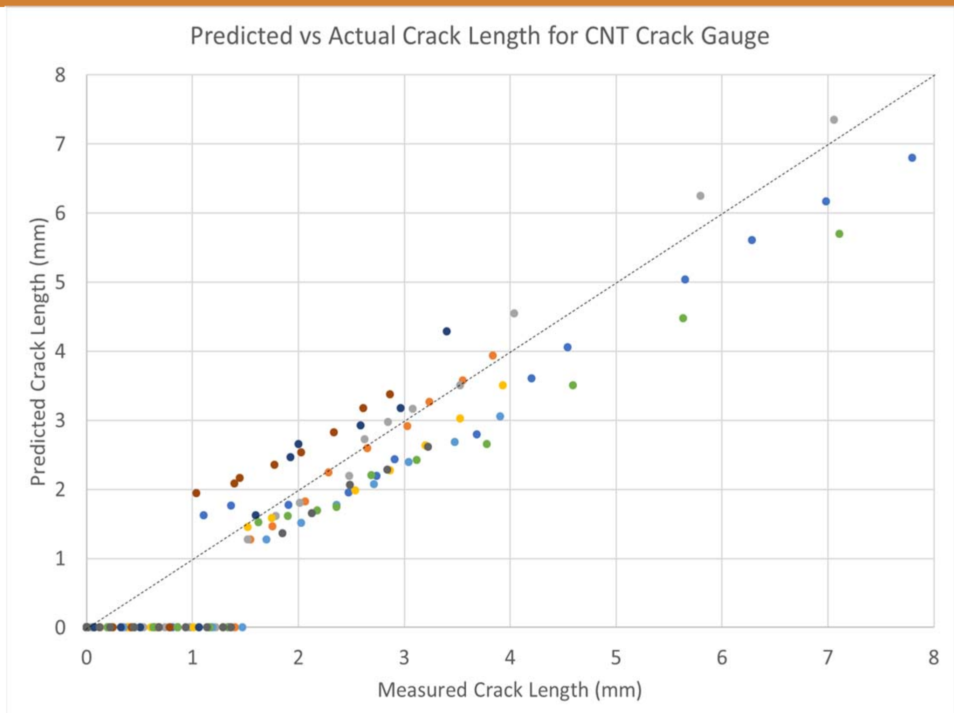


POD – Data < 5mm

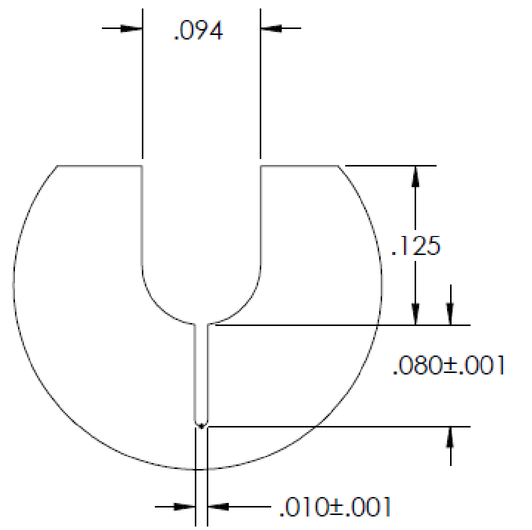


- **Density Plots of Bayesian Estimation Results**
- **REM provides an $a_{90/95}$ of 1.32 mm using all data (up to 18 mm)**
- **$a_{90/95}$ improves to 1.01 mm when only considering data < 5 mm**

PD Method Blind Detection Sensitivity Evaluation at FAA Tech Center

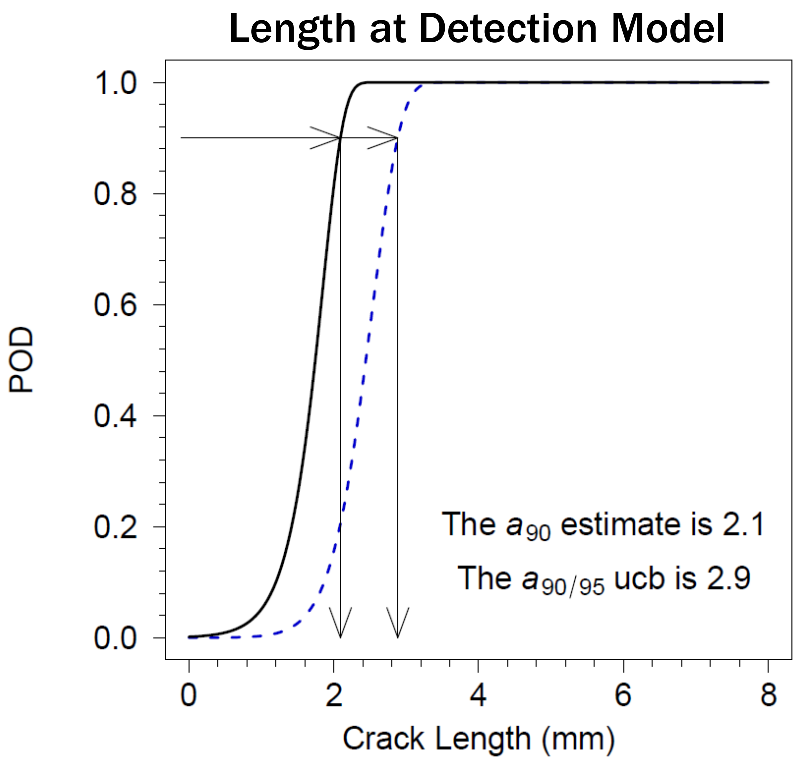


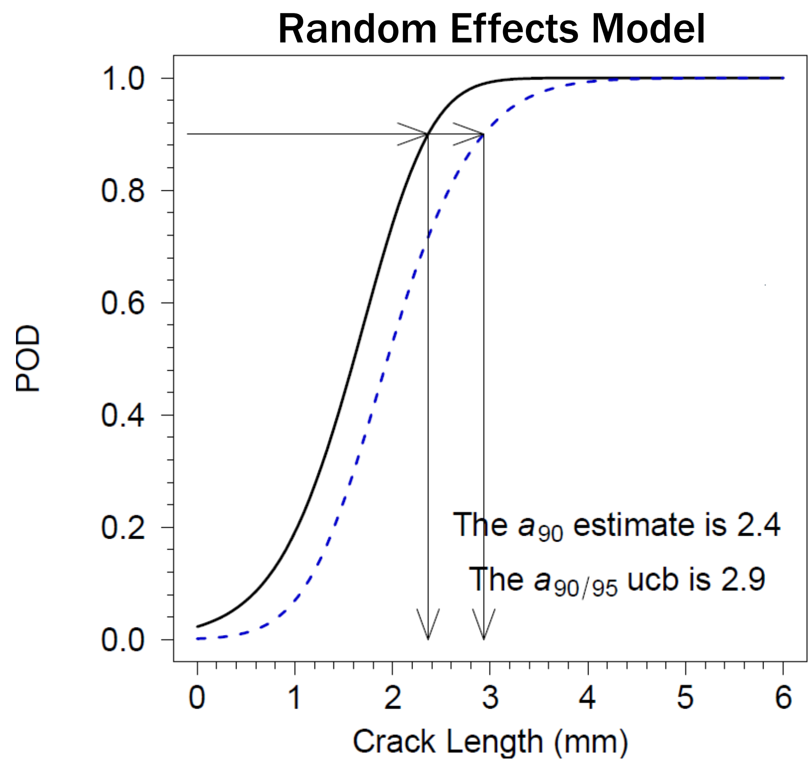
EDM Notch (inches)



- 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

Blind PD Method 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, variability of fatigue heating suspected**

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

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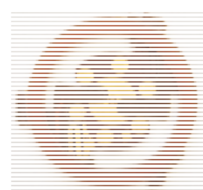
Example Case 2: Guided Wave (GW) Damage Detection (GLOBAL)

- 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

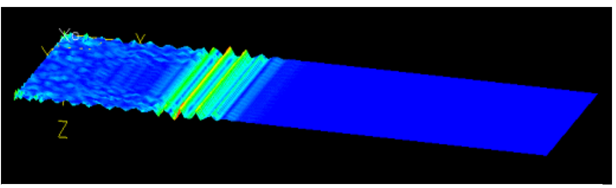
- During presented work, a PZT beamforming array was used
  - Central 6 mm ∅ actuator surrounded by six 3 mm ∅ sensors (spaced 60°)
  - Narrowband linear 50 - 250 kHz sinusoidal chirp excitation at 20Vpp

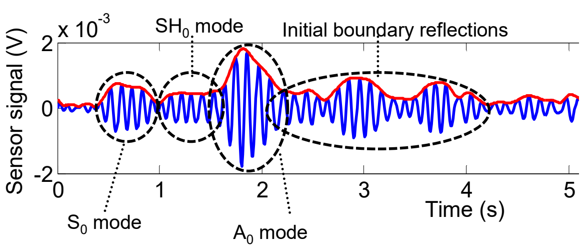
↕ 15 mm

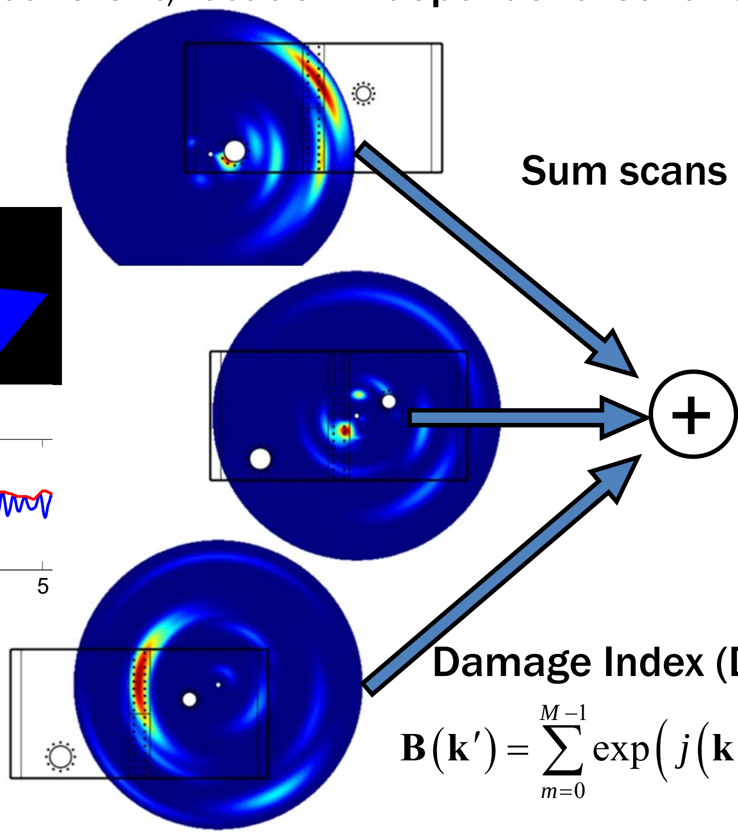


GW Method Beamforming PZT Array for Damage Detection

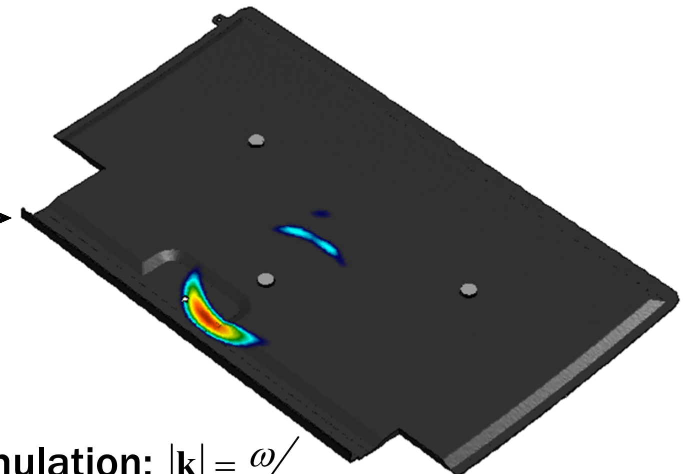
Each node processes phase-coherent, location independent "sonar-scan"







Sum scans incoherently to form composite image



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

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

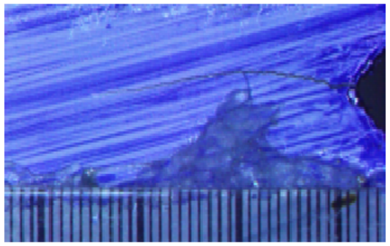
$\mathbf{k}$ wavenumber
ω temporal frequency
c_p A_0 phase velocity

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

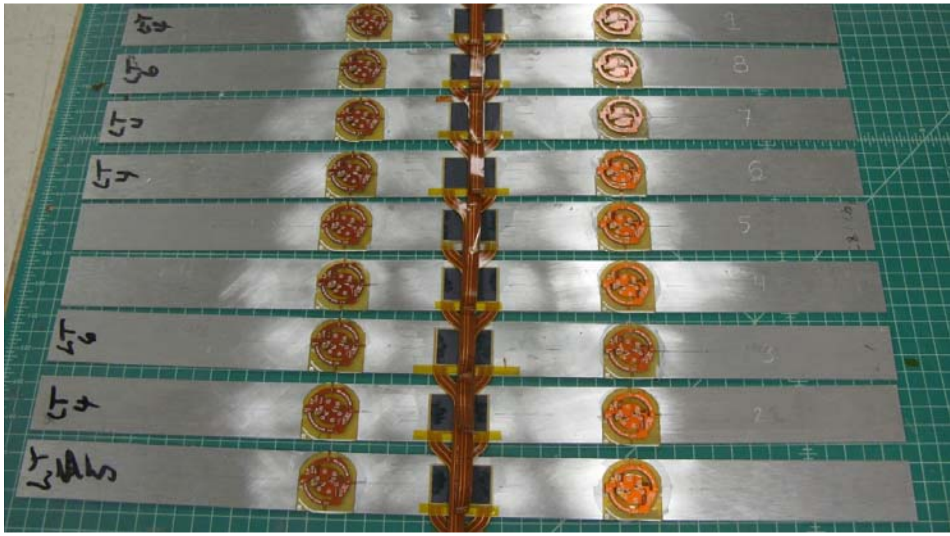
GW Method Detection Sensitivity Assessment Experiments

- **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

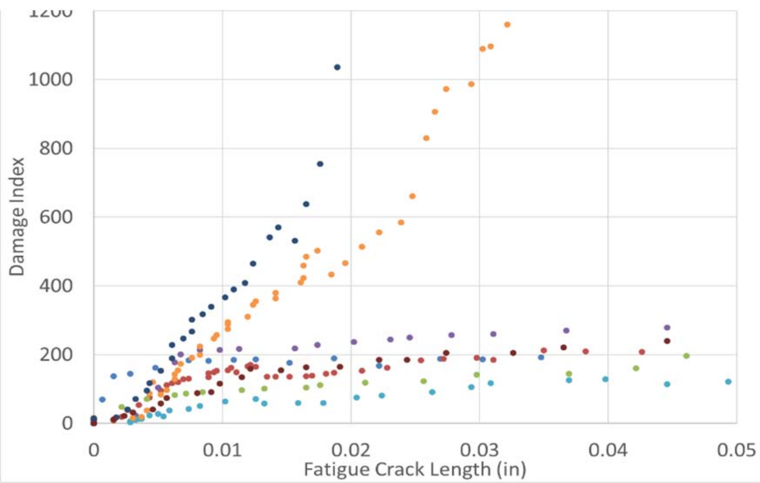


Data Acquisition Hardware

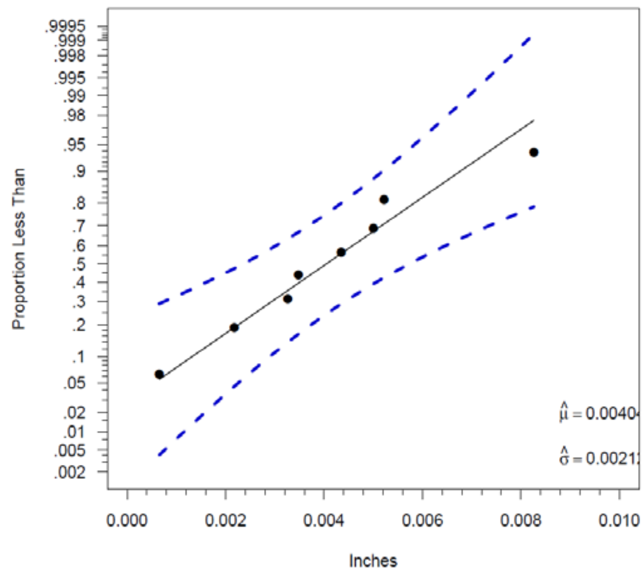


GW Method Detection Sensitivity using LaD Model (4-Point Bending)

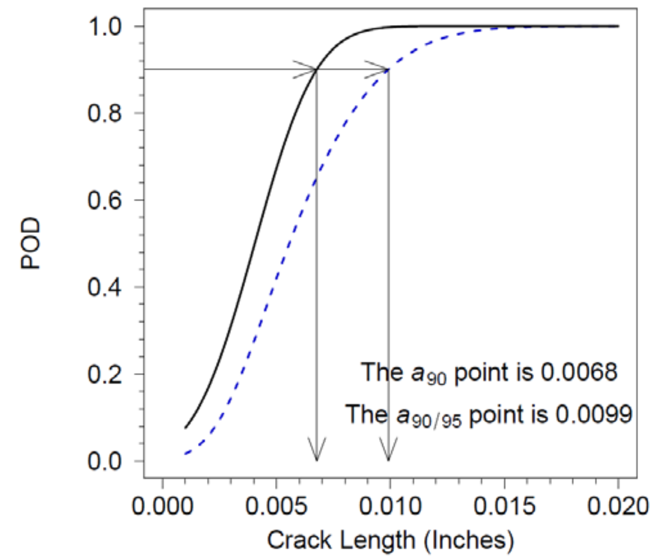
Pitch-Catch Energy Metric vs Crack Length



Gaussian Probability Plot



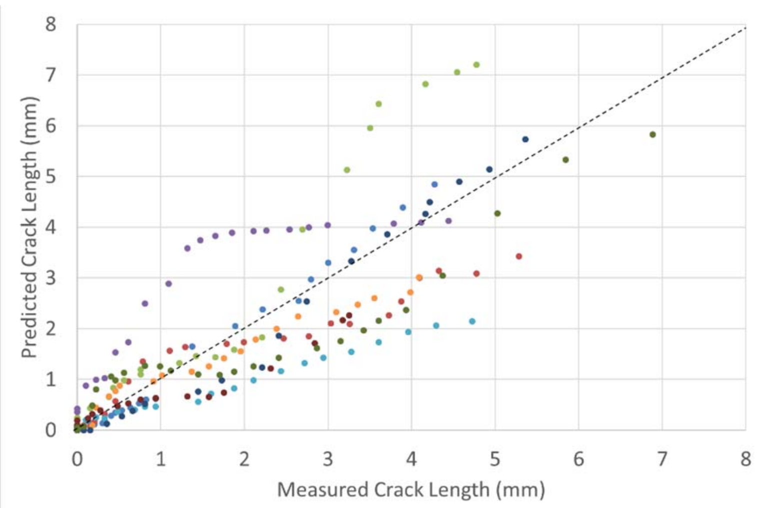
Sensitivity using LaD



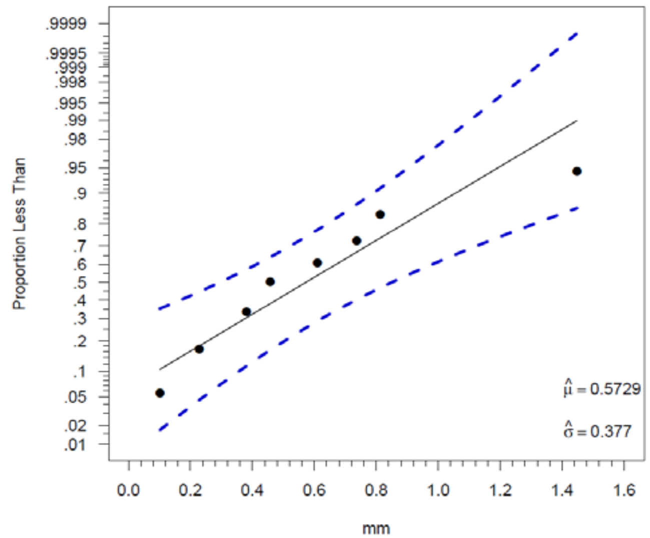
- GW detection data is best fit by a Gaussian distribution
- LaD provides an $a_{90/95}$ of 0.25 mm based on data *up until detection*
- Did observe odd phenomenon after detection w/DI's following 2 diverging trends

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

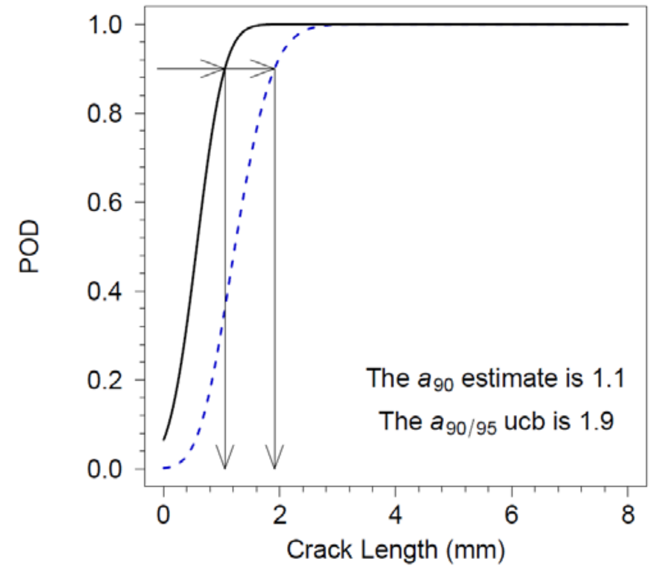
Predicted vs Measured Crack Length



Gaussian Probability Plot



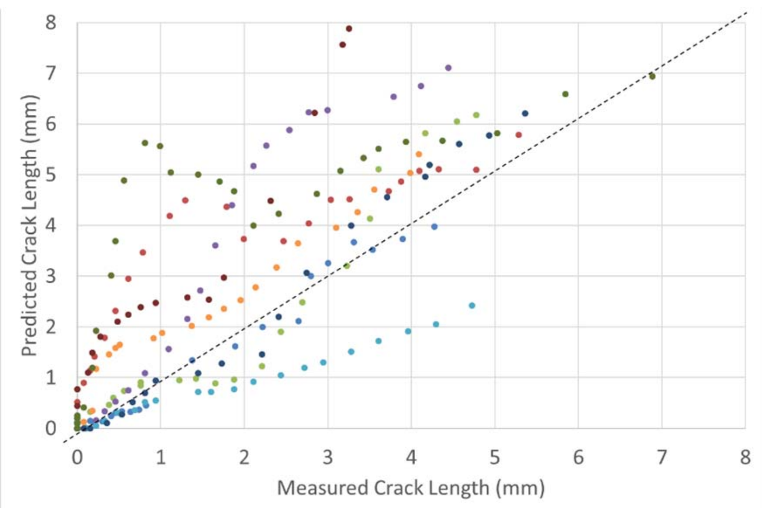
Sensitivity using LaD



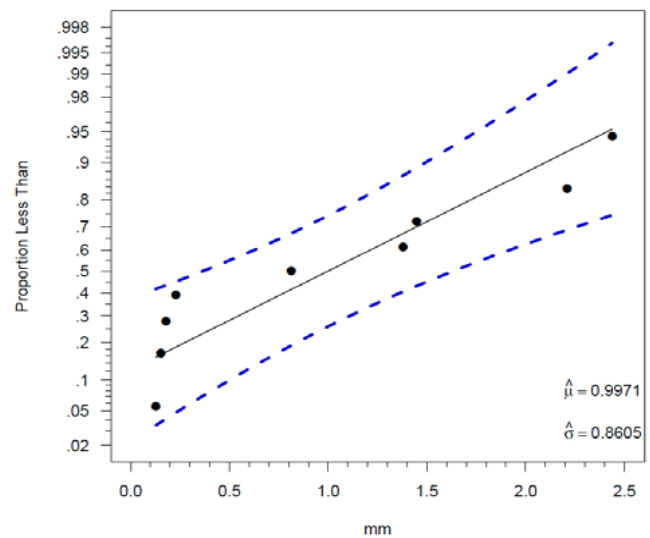
- Pitch-Catch (PC) data using PZT pairs on either side of EDM notch
- Able to produce better accuracy with additional sensor paths
- Analysis of PC data yields an $a_{90/95}$ value of 1.9 mm

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

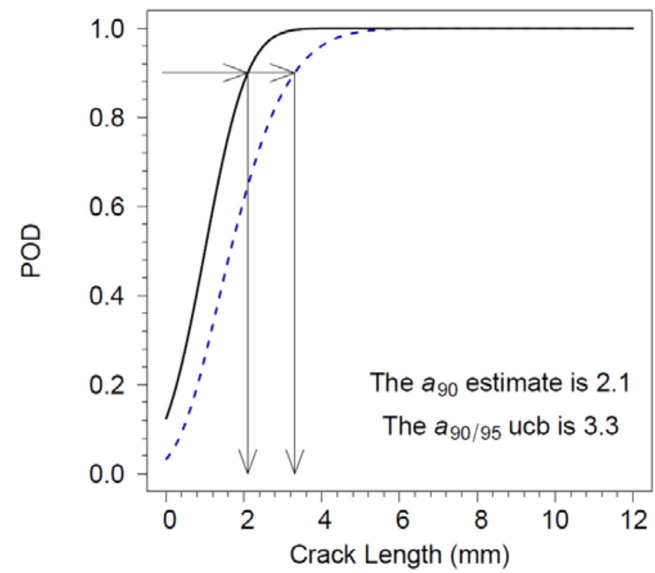
Predicted vs Measured Crack Length



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

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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

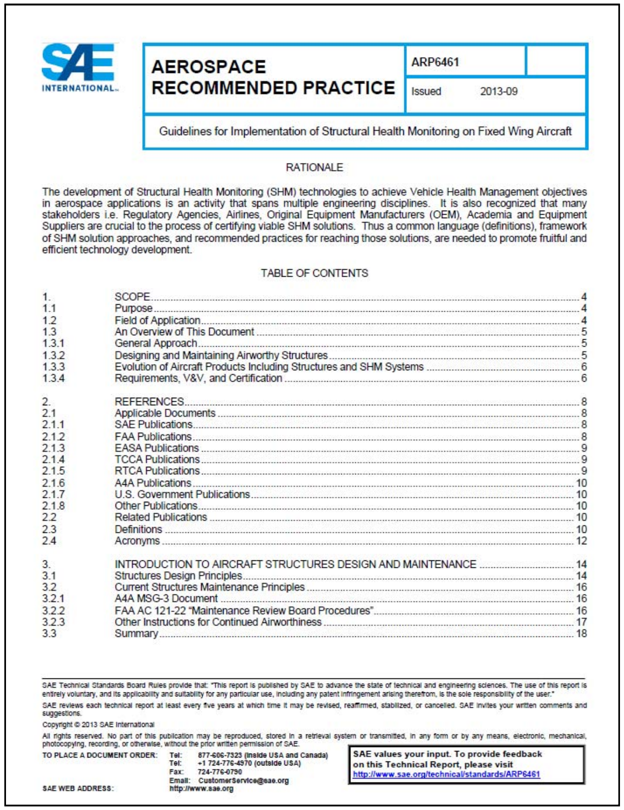
- **Need much more data to *validate* alternative SEPOD approaches vs MIL-1823A**

Aerospace Industry Steering Committee for SHM

- AISC-SHM is organized under SAE International
  - Under the supervision of the Aerospace Council
  - Reliability, Supportability & Health Management Systems Group
  - Follows guidance from the IVHM Steering Group
- Goal to facilitate implementation of SHM through development of standards & guidelines
  - Have met regularly twice a year for 13 years, alternate US & abroad
  - 1st meeting of AISC-SHM hosted by Stanford University (Fall 2006)
  - 28th meeting of AISC-SHM hosted by Safron in Paris (Spring 2020)
- Committee has over 150 members in various capacities
  - Average meeting has ~50 attendees from 4 continents
  - OEM, integrators, technology providers, airlines, academics, expert consultants
  - Regular participation from FAA, EASA, NASA, US military aviation representatives

SAE International Aerospace Recommend Practice (ARP) 6461

- "Guidelines on Implementation of Structural Health Monitoring on Fixed Wing Aircraft"
  - ➢ Published by AISC-SHM committee September 2013
  - ➢ Original mission to provide an approach for standardizing of SHM
  - ➢ Document represents combined views of all major aircraft OEM
  - ➢ ARP has been vetted by commercial, military & government experts
  - ➢ Address hardware, integration & validation requirements for SHM
- SAE ARP-6461 does not provide:
  - ➢ Details of specific SHM technologies or providers
  - ➢ Details for specific aircraft systems
  - ➢ Instructions for qualification & certification
- Other documents to be published soon
  - ➢ AIR6245 – Integration of SHM into Fixed-Wing Military Aircraft
  - ➢ AIR6892 – Guidelines for Implementation of SHM on Rotorcraft
  - ➢ ARP6461A – Updated version anticipated in 2020
  - ➢ ARP6821 – Guidance for Assessing Detection Capability for SHM



SAE INTERNATIONAL

AEROSPACE RECOMMENDED PRACTICE	ARP6461
	Issued 2013-09
Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft	

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 i.e. 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 SHM solution approaches, and recommended practices for reaching those solutions, are needed to promote fruitful and efficient technology development.

TABLE OF CONTENTS

There are no Regulatory Roadblocks for SHM in Commercial Aviation

- Existing damage-tolerant mindset presumes a scheduled task-based approach
  - Design philosophy considers range of threats generally without regard to likelihood of occurrence
  - Aerospace OEM define means & schedule for compliance with approval from FAA/EASA
  - Lack of SHM familiarity may lead to unclear/inconsistent regulatory requirements levied on applicants

- Three primary aspects for certification
  - System qualification using existing requirements
    - Defining the declared application intent
    - Determining the appropriate criticality
    - Applying 25.1301, 25.1309 integrity requirements
  - Protocols to validate certification credit
  - Instructions for Continued Airworthiness using existing requirements

- Presently multiple application pending at the FAA for pilot SHM implementations

Commercial Aircraft OEM Plans for Implementation of SHM

- A4A MSG-3 outlines process for determining initial scheduled maintenance requirements
  - Means for developing maintenance tasks/intervals acceptable to regulatory, operators & manufacturer
  - SCHEDULED SHM (S-SHM): Structure inspection tasks for accidental, environmental and/or fatigue damage replaced by a scheduled interaction with a SHM device at fixed intervals
  - AUTOMATED SHM (A-SHM): No pre-determined interval at which maintenance action must takes place, but instead relies on the SHM system to inform maintenance personnel that actions must take place
- Follow stepwise implementation for credit validation
  - Initially focus on S-SHM using existing NDT intervals & direct comparison with NDT results
  - Prove SHM sensitivity & reliability to damage type though seeded tests & on-aircraft trials
  - “Controlled Introduction to Service” to gain confidence
  - Lead fleet monitoring, establish robust feedback loop
- Introduce S-SHM in parallel with existing NDT to gain additional in-service validation

Commercial Aircraft OEM Timeline for Implementation of SHM

Near Term

- Replace inspection tasks w/SHM to reduce maintenance burden
- Flexible maintenance intervals via operational monitoring using existing sensor capabilities
- Assess conditional events w/SHM

Mid Term

- Integrated SHM solutions for conditional maintenance
- Enable SHM based optimized design & weight savings
- Certification of maintenance credit

Long Term

- Optimize design rules for maintenance philosophy based on SHM monitored structures
- Airframe life-extension

Acknowledgments

- AISC-SHM (member organizations contributed content & images for several slides)
- Collins Aerospace (collaborator for GW method hardware)
- Analog Devices (collaborator for PD method hardware)
- US Air Force (funding under FA8650-15-C-2563 & FA8501-15-C-0025)
- FAA William J. Hughes Technical Center (collaboration under ANG-TT-CRDA-0352)
- Individual contributors to presented work
  - ➢ Mr. Paul Swindell (FAA & chair of AISC-SHM Reliability Working Group – driving SEPOD research)
  - ➢ Prof. Bill Meeker (Iowa State University – all statistical analysis presented)
  - ➢ Dr. Gregory Jarmer (Metis Design Corporation – all GW method results presented)

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