Detection Sensitivity Analysis for a Guided Wave (GW) Structural Health Monitoring System

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structural health monitoring
multi-functional materials
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Introduction

- SHM uses permanently integrated non-destructive sensors
  - Many viable strategies for measuring local or global damage
  - Guided Wave (GW) methods use piezoelectric actuators/sensors to detect changes/reflections in ultrasonic wave propagation

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

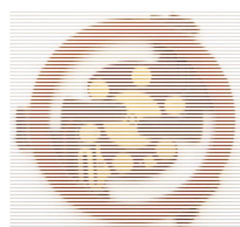
- Challenging to obtain $a_{90/95}$ for SHM using traditional approaches
  - Expensive due to permanent sensor installation, need for many specimens
  - Traditional approaches do not allow for repeated inspections as flaw grows
  - Length at Detection (LaD) developed at Sandia as an alternative approach

Guided Wave (GW) Damage Detection

- 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

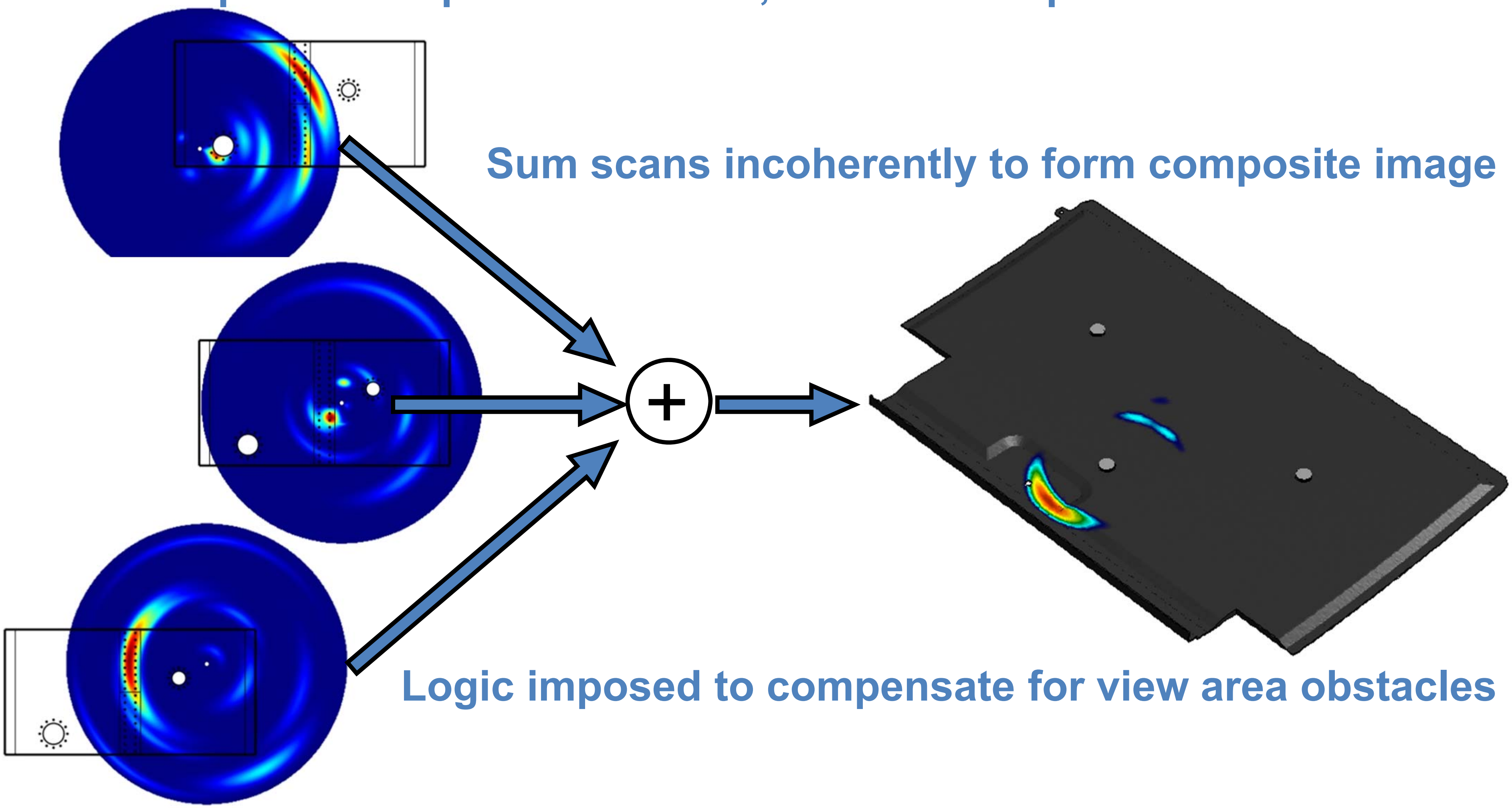
↕ 15 mm



Beamforming PZT Array for GW Detection

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

Sum scans incoherently to form composite image



Logic imposed to compensate for view area obstacles

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

GW Damage Metric Formulation

- Signal processing
  - ➢ Bandpass filtering of acquired signal (80 kHz center frequency)
  - ➢ Baseline waveform from pristine condition is subtracted from filtered signal

- Detector is a phased array beamformer for the A_0 guided wave
  - ➢ Theoretical dispersion curves solved numerically
  - ➢ Beamforming applies appropriate phase shift for an assumed propagation direction to coherently align & then sums array signals
  - ➢ Beamforming performed over all possible arrival angles for a signal
  - ➢ Maximum value over all angles is taken as an estimate of crack size

- Repeated for every pitch-catch (PC) & pulse-echo (PE) pair
  - ➢ Estimates from array paths pairs averaged yield damage index (DI):

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

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

Experimental Setup for 4-Point Bending Fatigue

- Total of 8 Aluminum specimens tested
  - 300 x 25 x 3 mm bars
  - Loaded in 4-point bending, fatigued at 80% of yield strength
  - 50,000 cycles at room temperature

- Programable test fixture
  - LabVIEW software used to automate cycling & data collection
  - Digital microscope used to capture truth data at ~1.5 micron resolution
  - GW data collected in unloaded positions every 1,000 cycles
  - Image of crack extending from tip of EDM notch captured along w/GW data
    - — usually optically detectable around 25 micron between 22,000 - 28,000 cycles

Data Acquisition Hardware

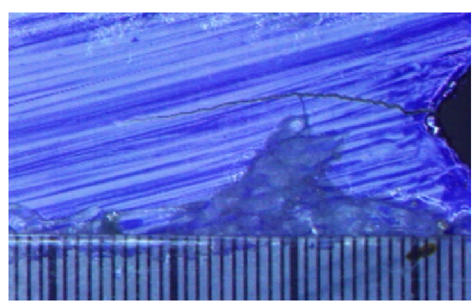


Image of Crack from EMD Notch

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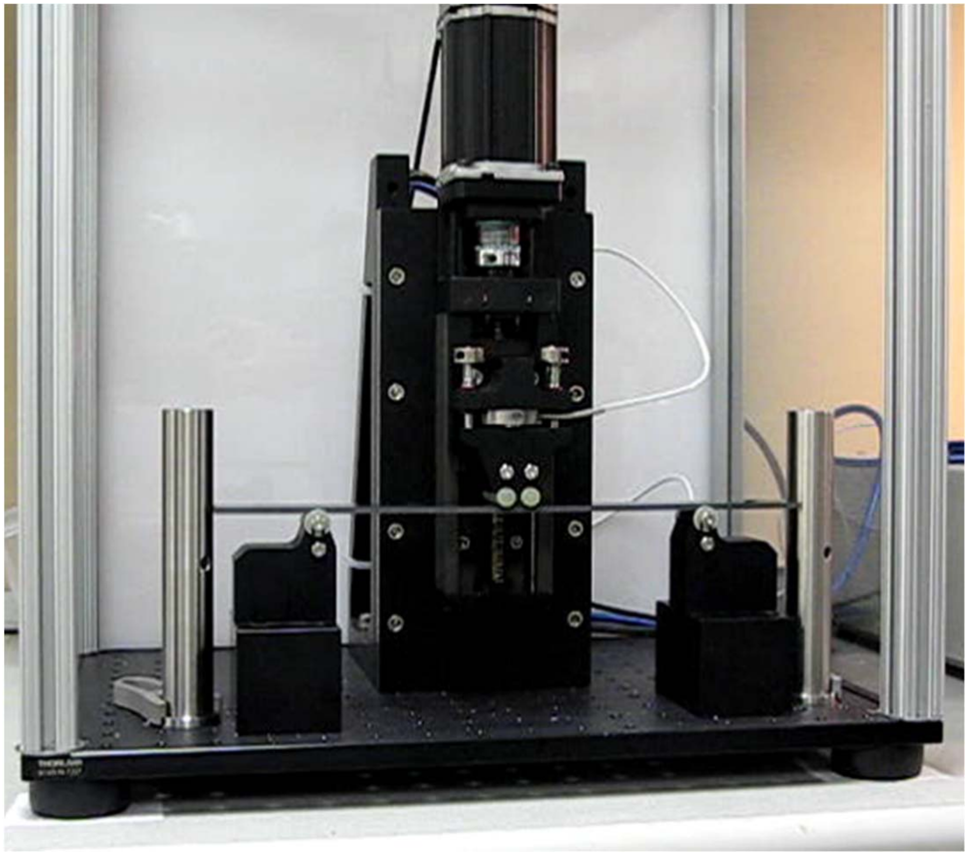
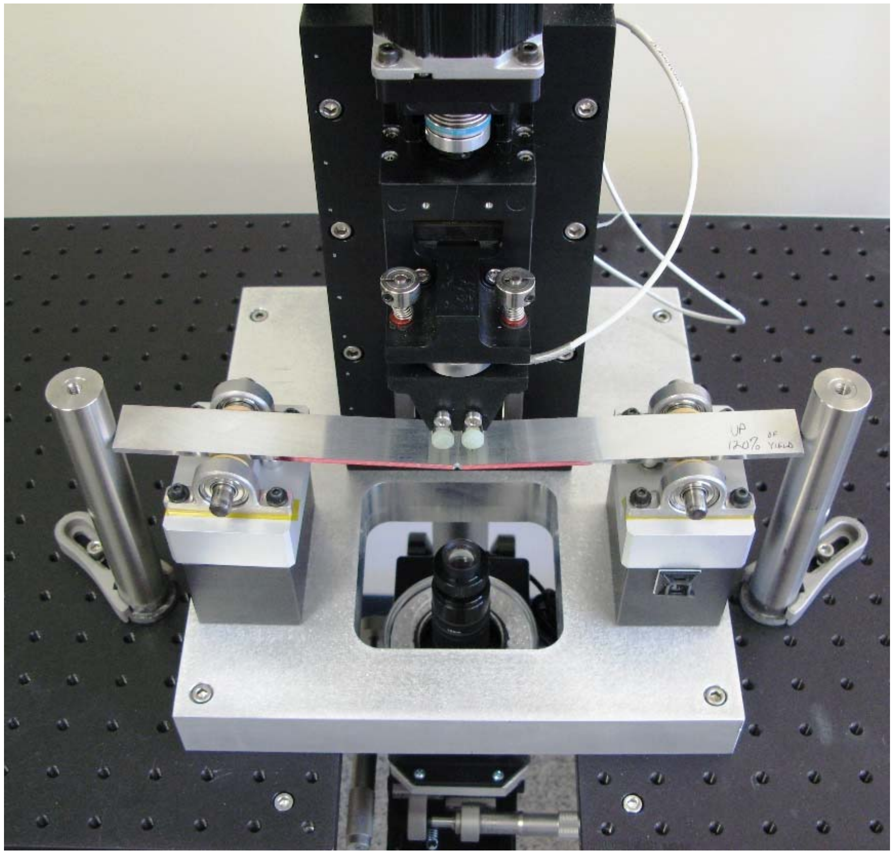
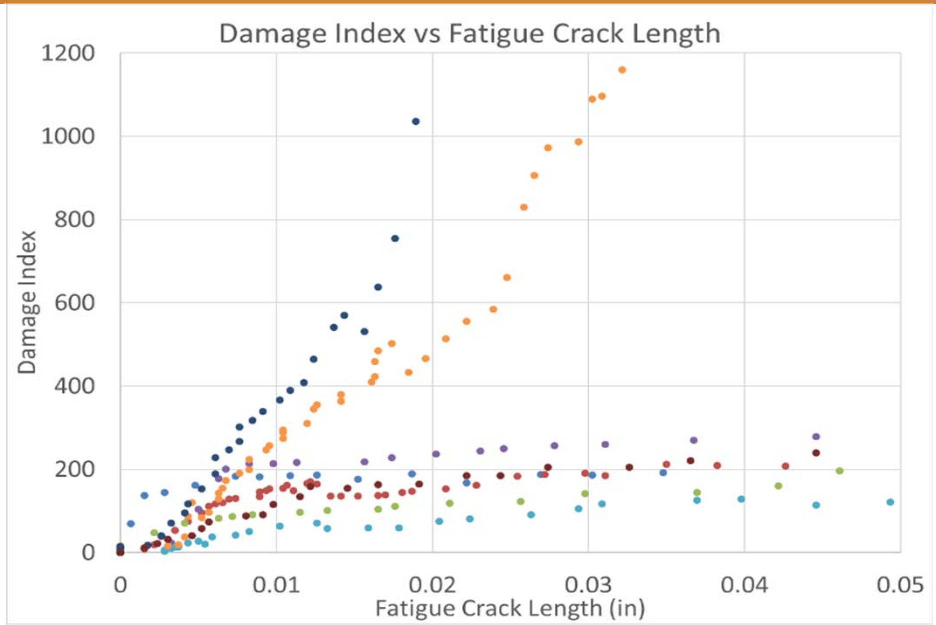
Automated 4-Point Test Bending Fatigue Fixture

- 25 mm between inner rollers, 200 mm between outer rollers
- Constant moment between inner rollers, 3300 $\mu\varepsilon$ (80% yield)
- Cycles at 1Hz while collecting load, stroke, temperature





GW Damage Index Results for 4-Point Bending



- **DI estimated for each set of GW cycle data**
  - ➢ **DI points for specimens plotted vs optically measured crack length**
  - ➢ **Threshold value was set at a DI value of 100**

- **Some DI values follow linear trend, other set appear to asymptote**
  - ➢ **May be related to in-plane & through-thickness crack paths**
  - ➢ **Appears to indicate strong correlation with both damage <u>length</u> & <u>shape</u>**

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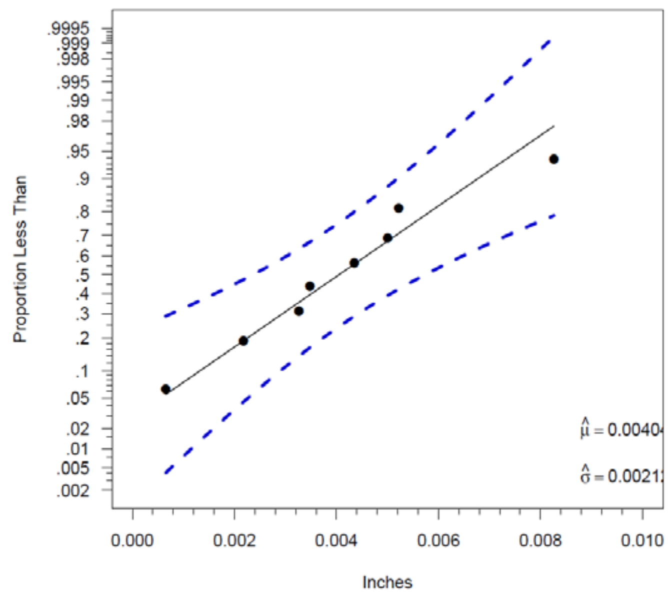
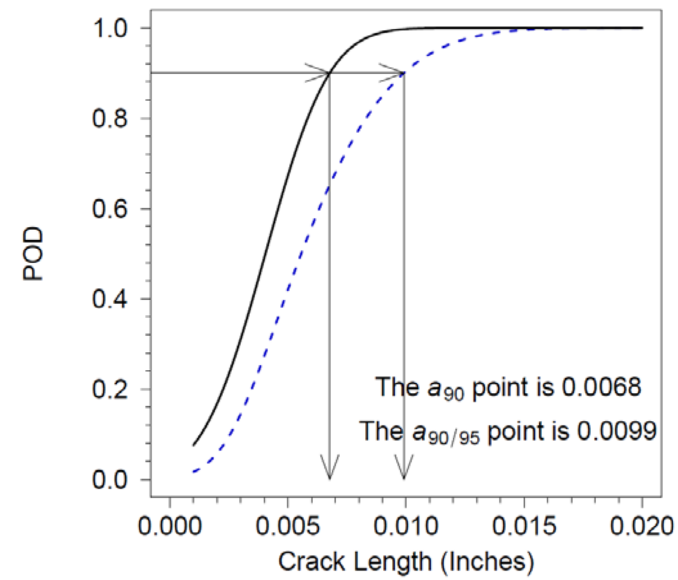
Detection Sensitivity: Length at Detection Method

Gaussian Distribution Probability

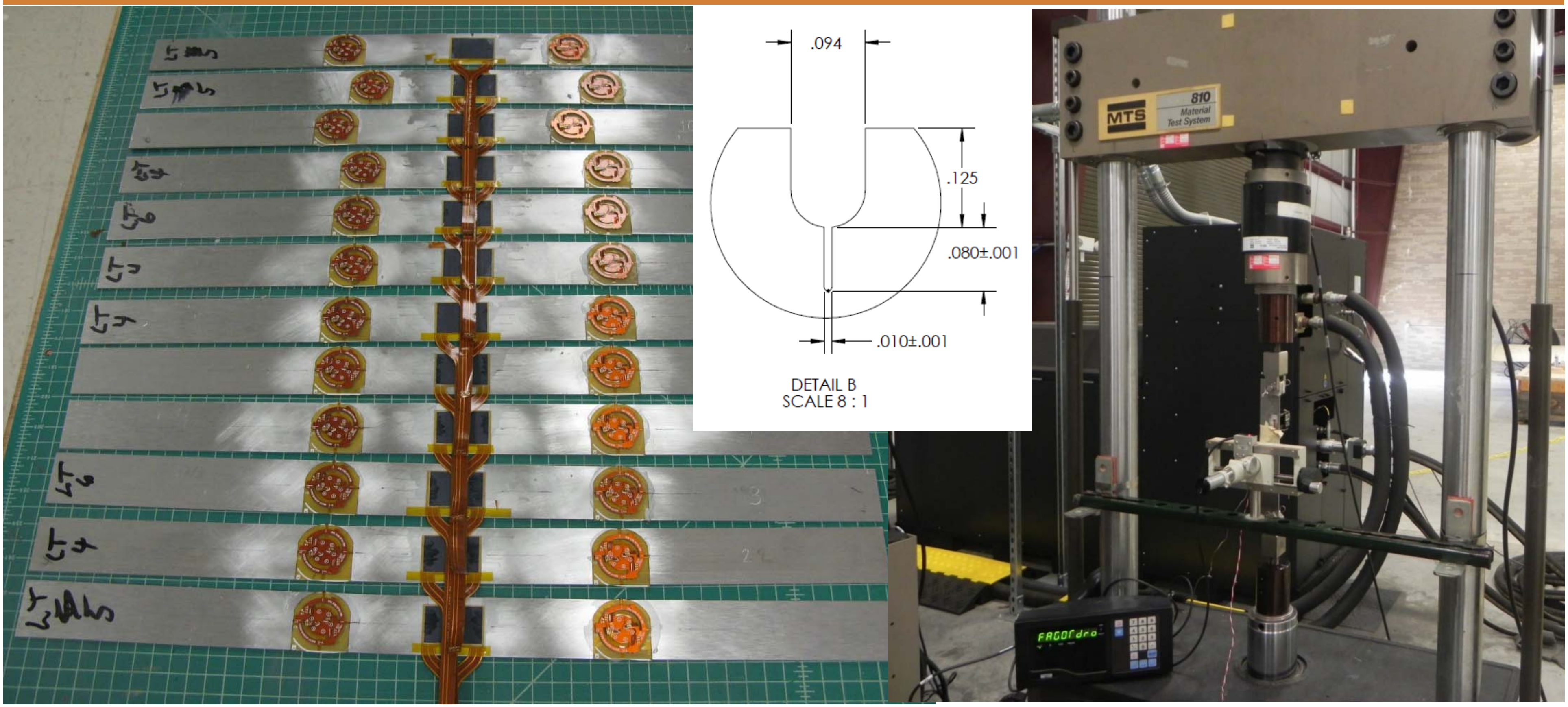


$a_{90/95}$ using LaD Model



- Detection sensitivity calculated by Prof. Bill Meeker at Iowa State
- LaD considers data until interpolated threshold crossing value
- Gaussian distribution provides best fit for results
- Analysis indicates an $a_{90/95}$ of 0.25 mm based on this data set

Blind Sensitivity Testing at FAA Tech Center



- Additional blind testing conducted through FAA CRADA
- Tensile-tensile fatigue tests on aircraft Al-Li bars with EDM notch
- Goal to further evaluate LaD for GW detection sensitivity

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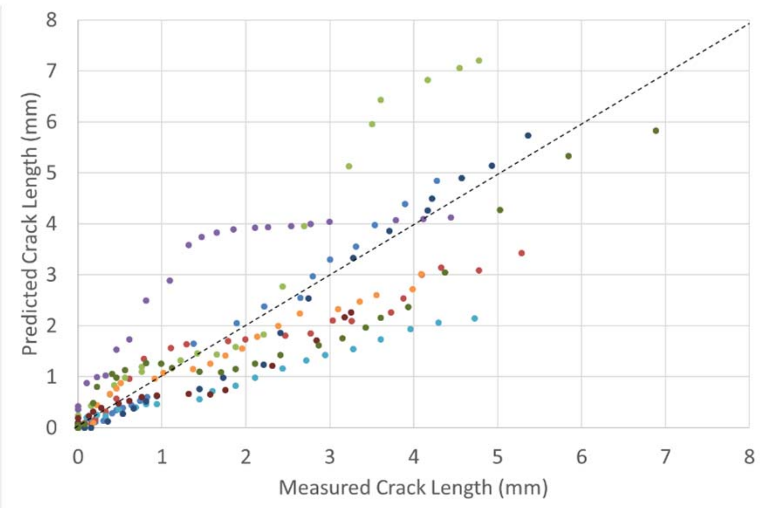
Experimental Setup for Blind FAA Testing

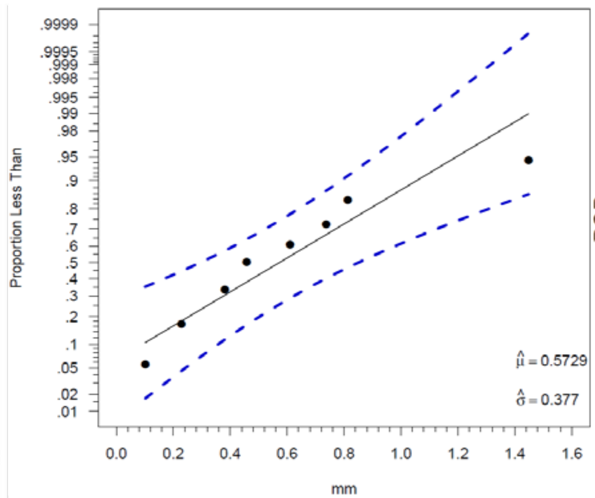
- Twelve 600 x 40 x 2 mm specimens cut from FAA-provided plate
  - 5 mm edge notch electrical-discharge machined (EDM) via ASTM E647
  - Sacrificial specimens used by FAA to determine appropriate load & rate
  - PZT sonar arrays installed offset by 90 & 115 mm from the EDM notch
  - CNT crack gauge also bonded (data is presented in a separate paper)
- Fatigue cracks grown through 35,000 tension-tension cycles
  - ~3 mm of crack growth, data collected every 1,000 cycles
  - Data collected using proprietary microminiature acquisition hardware
  - 3 sensors inadvertently damaged by FAA, were excluded from this study
- Only single specimen truth data provided for calibration purposes
  - Remaining data processed using linear scaling factor to estimate length
  - Same DI approached use as previous experiment, yields length vs cycle
  - Truth data measured optically, provided after crack predictions sent to FAA

Pitch-Catch Detection Sensitivity using LaD Method

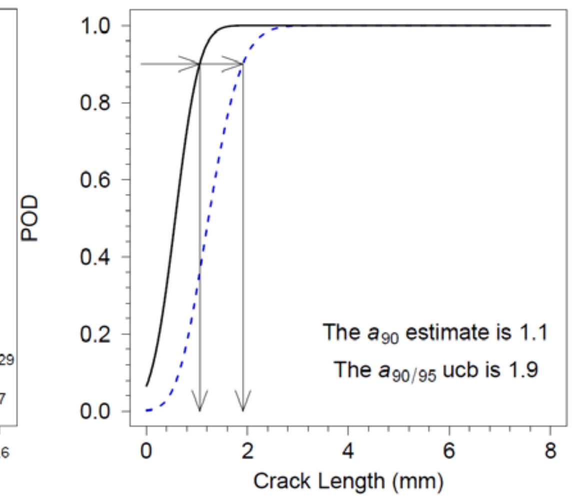
Predicted vs Actual Crack Length



Gaussian Probability



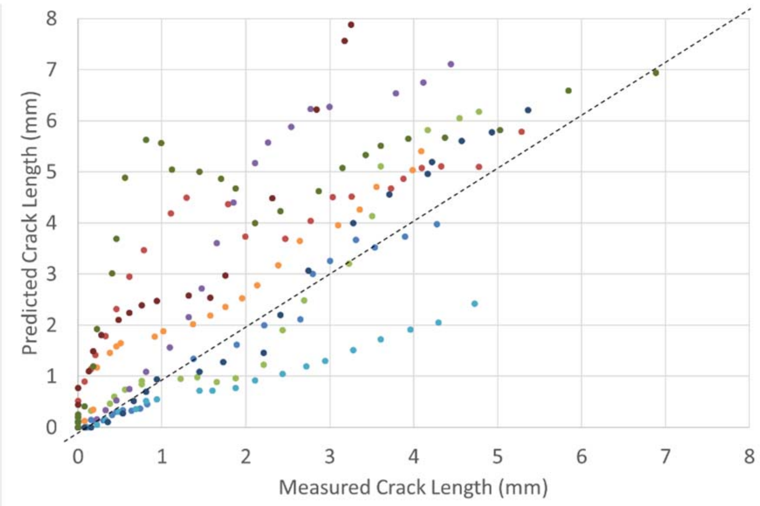
Sensitivity using LaD



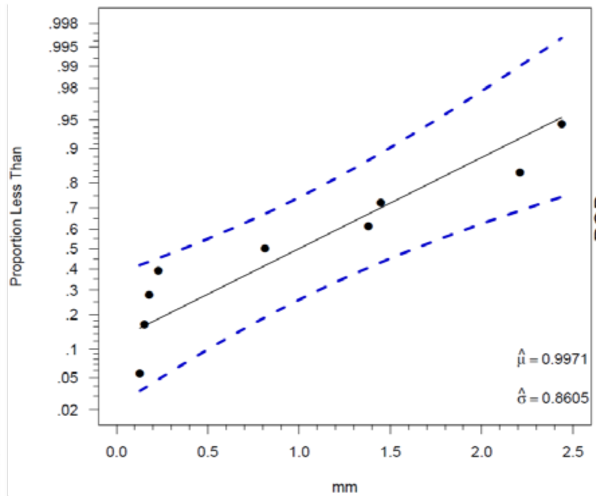
- Pitch-Catch (PC) data using PZT pairs on either side of EDM notch
- Able to produce better accuracy with additional sensor paths
- Statistical analysis performed by Prof. Bill Meeker at Iowa State
- LaD considers data until interpolated threshold crossing value
- Gaussian distribution provides best fit for results
- Analysis of PC data yields an $a_{90/95}$ value of 1.9 mm

Pulse-Echo Detection Sensitivity using LaD Method

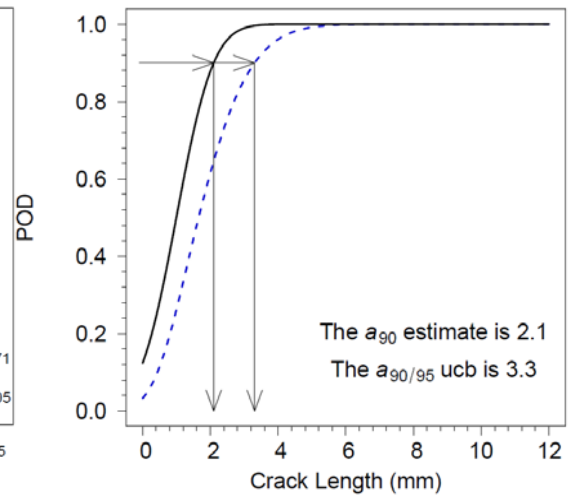
Predicted vs Actual Crack Length



Gaussian Probability



Sensitivity using LaD



- Pulse-Echo (PE) data using PZT data from sensors independently
- Advantage of only using one sensor array, better at boundaries
- Statistical analysis performed by Prof. Bill Meeker at Iowa State
- LaD considers data until interpolated threshold crossing value
- Gaussian distribution provides best fit for results
- Analysis of PE data yields an $a_{90/95}$ value of 3.3 mm

Summary & Future Work

- Investigation of detection sensitively for GW SHM method
  - 4-pt bending fatigue of Al beams funded through AFRL SBIR
  - CRDA with FAA for tensile-tensile fatigue of Al/Li beams
  - Collaboration with Prof. Meeker (Iowa State) for statistical analysis
  - Alternative statistical approach: Length at Detection (LaD) Model

- Initial detection sensitivity results encouraging
  - $a_{90/95}$ value of <1 mm for 4-point bending fatigue in controlled testing
  - $a_{90/95}$ value of 1.9 mm for pitch-catch (PC) data in blind validation testing
  - $a_{90/95}$ value of 3.3 mm for pulse-echo (PE) data in blind validation testing

- Future work
  - Need much more data to validate alternative approaches vs MIL-1823A
  - Analytical/FEA for model-assisted probability of detection (MAPoD)
  - Issue being investigated by AISC-SHM sub-committee, new SBIR topic

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