# An Acoustic Emission Approach to Assess Remaining Useful Life of Aging Structures under Fatigue Loading

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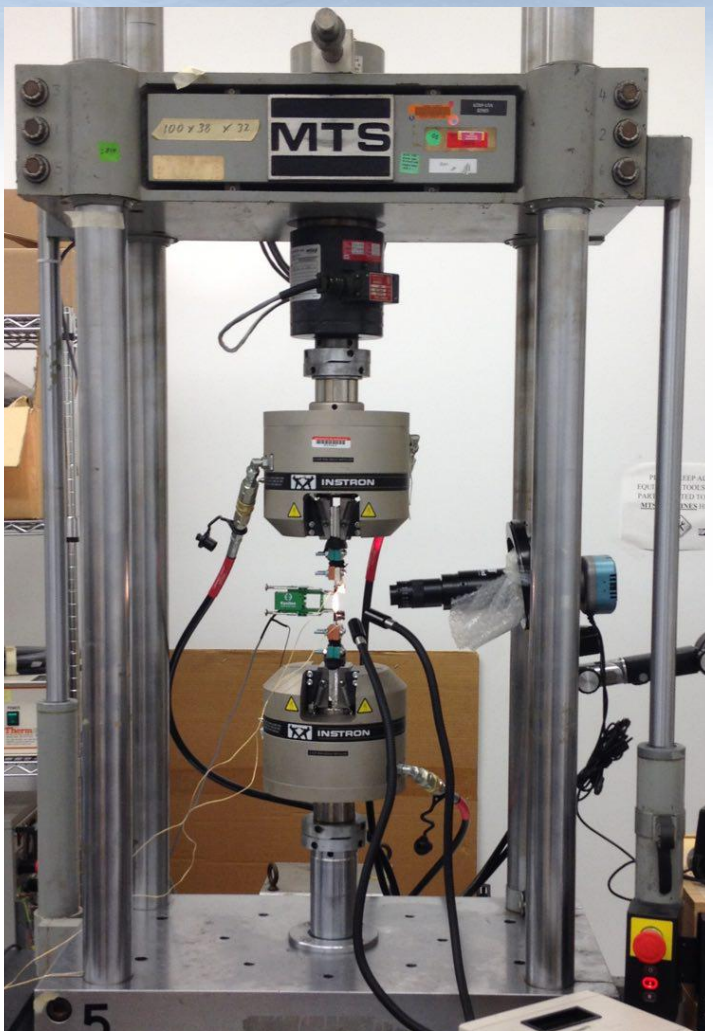
Risk and Reliability

# Outline

- Objective
  - Motivation, acoustic emission (AE) background, approaches
- Test setup and Accomplishments
  - Test setup
  - Sample geometry
  - Denoising strategies
  - Entropy Approach
- Future Works
- Publications & Personnel
- Questions & Answer



# Motivation and Goal (1/1)

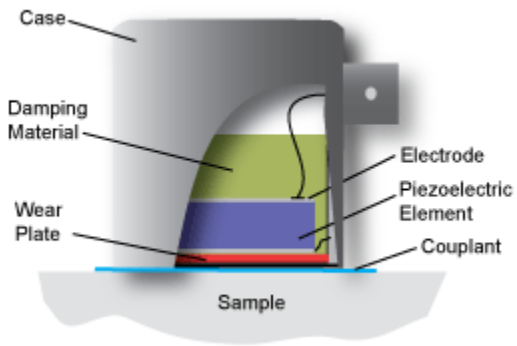
- Motivation
  - Airframe see cyclic loading
  - Susceptible to fatigue crack
  - Full-Scale Fatigue Testing (FSFT) estimate service life, requires long time, high cost and life is underestimated
  - NDE methods can inspect and detecting fatigue cracks
  - Fatigue life before crack initiation is comparably long
  - Estimation of damage before crack formation is ideal


Full-scale fuselage testing from Southwest Research Institute

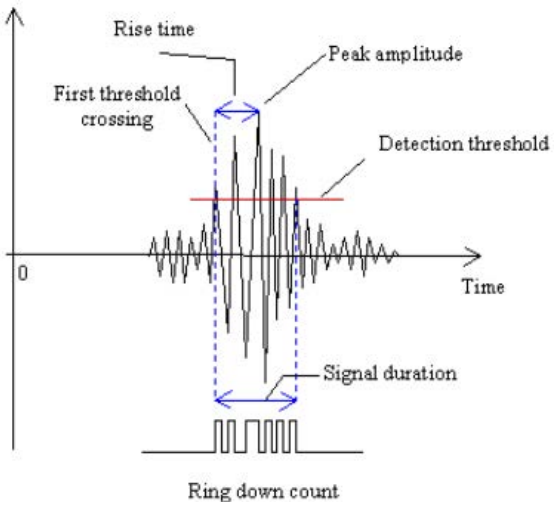
- Goal of this project
  - Develop models for estimating NDE-based incipient crack damage using AE

# AE Background (1/2)

- Acoustic Emission (AE) - **Concept**
  - Transient elastic wave generated by the rapid release of energy within the material
  - AE sensors use piezoelectric element to transform resonance displacement to electric signal
  - When hit the threshold, collects signals inform of counts, energy, and waveform



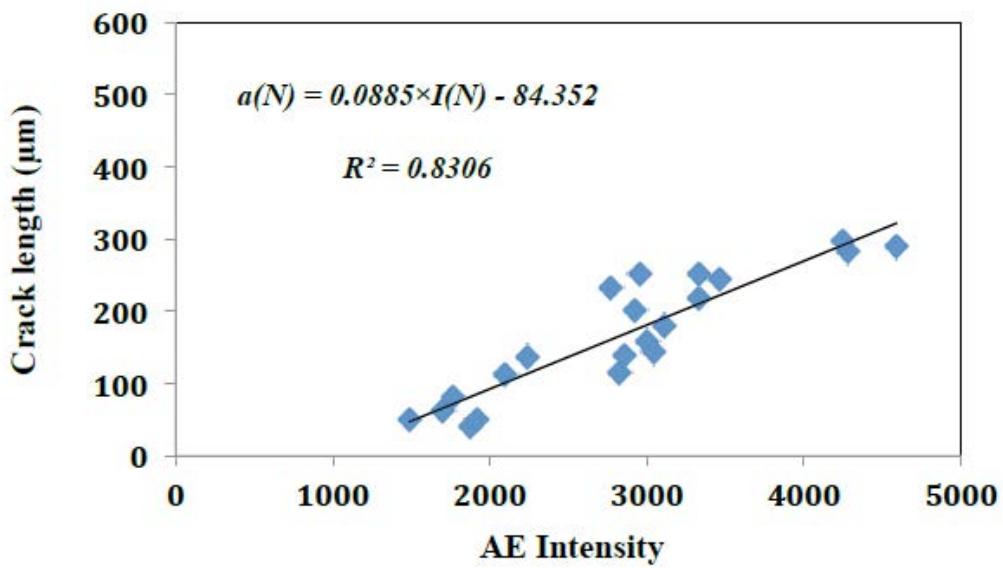

AE sensor
< https://www.nde-ed.org, 10/02/15>




AE waveform and parameters

# AE Background (2/2)

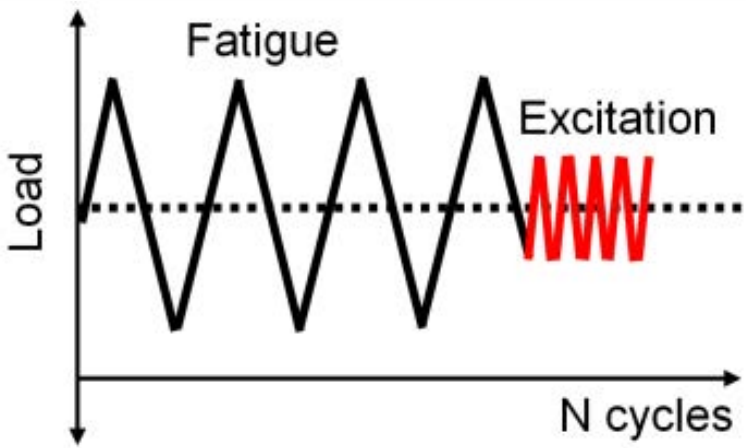
- Acoustic Emission (AE) - **Damage correlation**
  - We have found that crack initiation and propagation can be correlated by using AE parameters for small and large sized cracks
  - For small crack, AE Intensity and crack length presented linear relationship
  - However, damage state before crack initiation has not well been measured

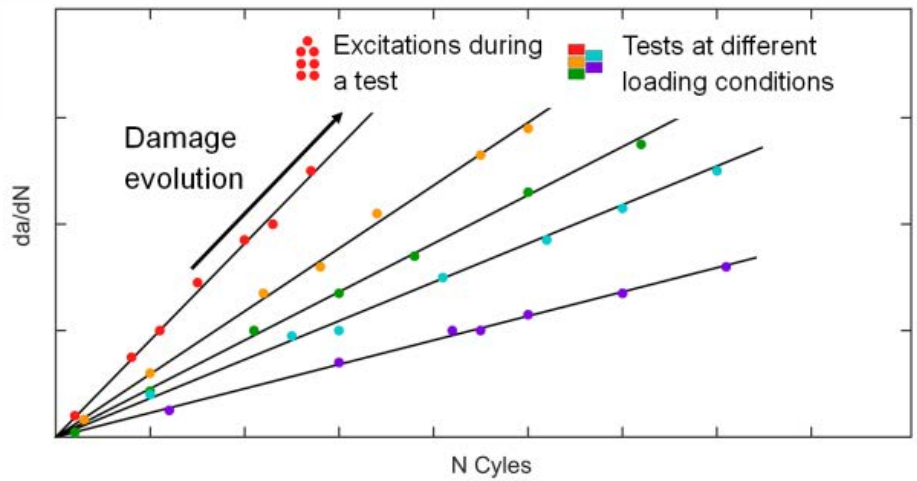



* Keshtgar, Azadeh (2013) Acoustic Emission-Based Structural Health Management and Prognostics Subject to Small Fatigue Cracks, Ph.D. Disseration, Department of Mechoanical Engineering, University of Maryland

# Approaches (1/1)

- Approach
  - Characterize AE parameters (raw or processed) correlation with material damage state before crack initiation
  - Supplement AE parameters with additional indications, e.g. thermal gradient and strain energy
  - Develop application method to Short-Time Loading Process (STLP)

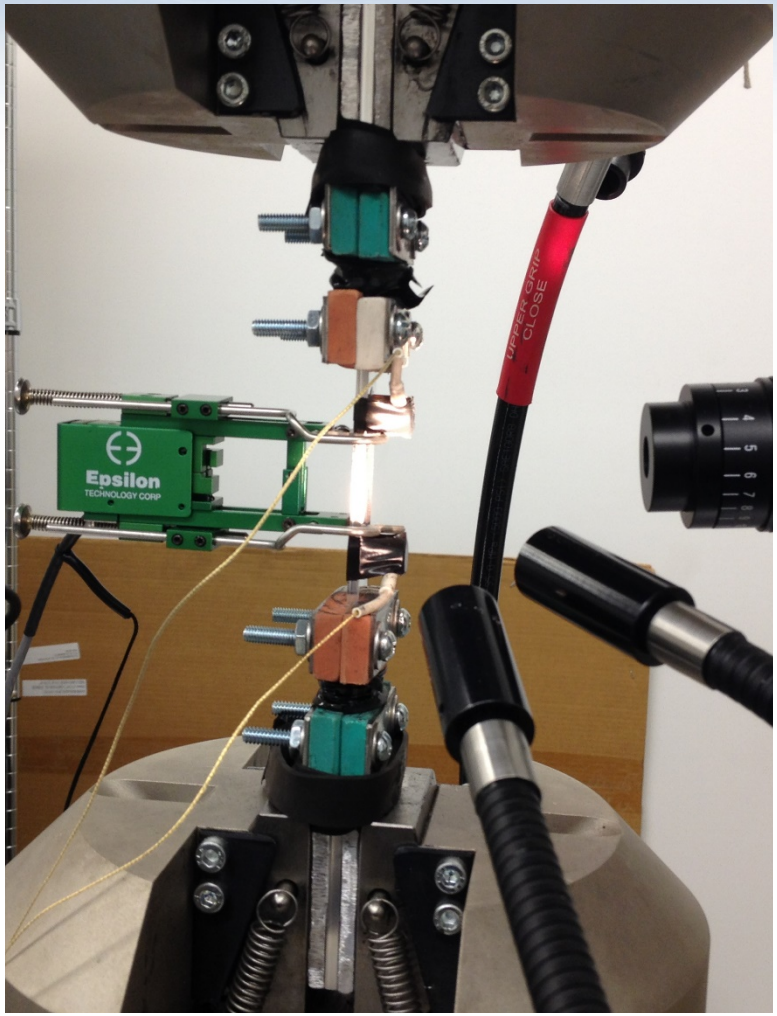


# Test Setup (1/1)

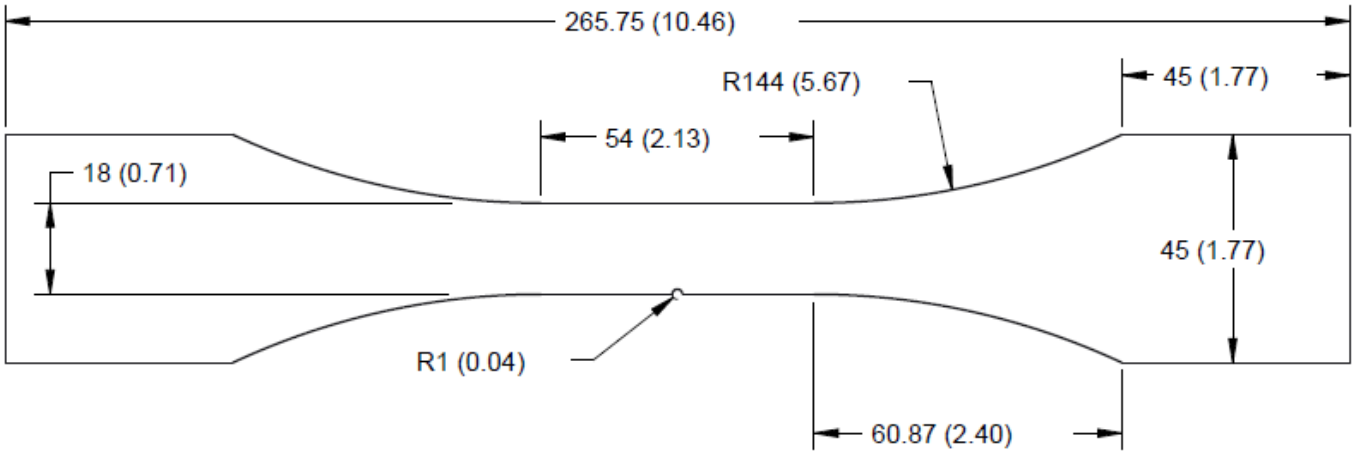
- Loading conditions
  - Cyclic fatigue
  - Maximum load = 10-20 kN
  - Frequency = 2-5 Hz
- Instruments and components
  - Specimen
  - AE sensors and acquisition system
  - Extensometer
  - Light source
  - Microscope
  - Damping material
- Measurements
  - *Stress and strain (DIC and extensometer)
  - *AE signals
  - *Real-time magnified images
  - 200x mag. images of surface before and after test
  - Considering IR thermal image captures

**Denotes synchronized measurements*



# Sample Geometry (1/1)

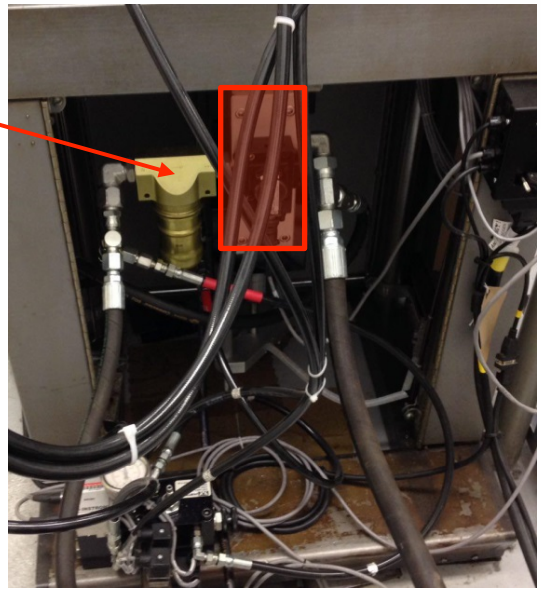
- Sample material
  - AA 7075-T6
  - Specimens manufactured from same large plate
- Sample geometry
  - Dog bone geometry with round notch
  - Follows ASTM E466 standard
  - Relatively large sample size to accommodate all on-specimen components



# Denoising Strategies (1/5)

- Why denoising?
  - Noise signals from testing machine conflict with damage signals
  - MTS load frames are notorious for high-amplitude noise signals
  - Typical noise AE amplitudes: 35-45 dB, but detected AE amplitude: ~65 dB
  - Noise is typically filtered out by setting AE threshold above noise amplitude
  - If threshold is set above 65 dB, no all damage-related AE signals will be captured
  - Three denoising categories cosnsidred: noise source elimination, mechanical damping, and software filtering

Moog servo valve housing

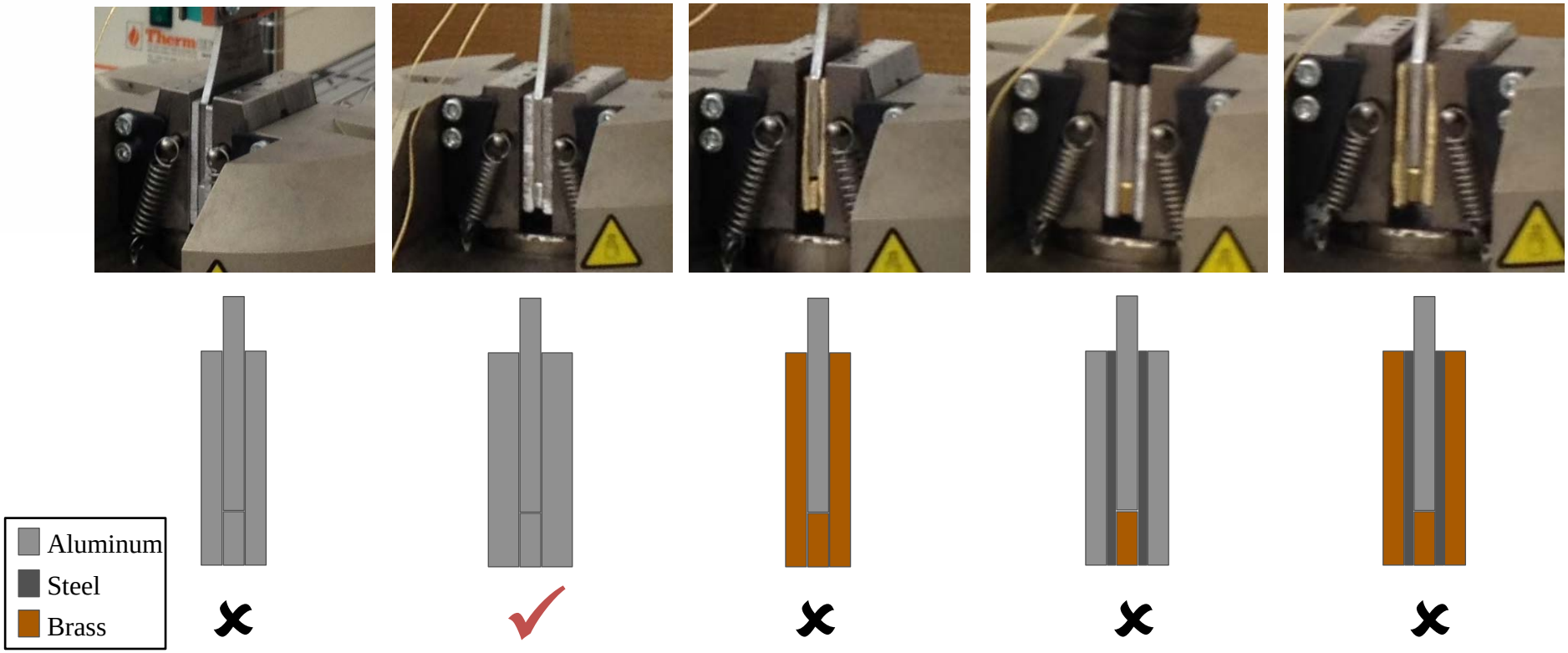


Behind the MTS Machine

- Noise source elimination
  - Moog servo valve a major source of noise
  - Highlighted housing records high vibrations: ~95 dB

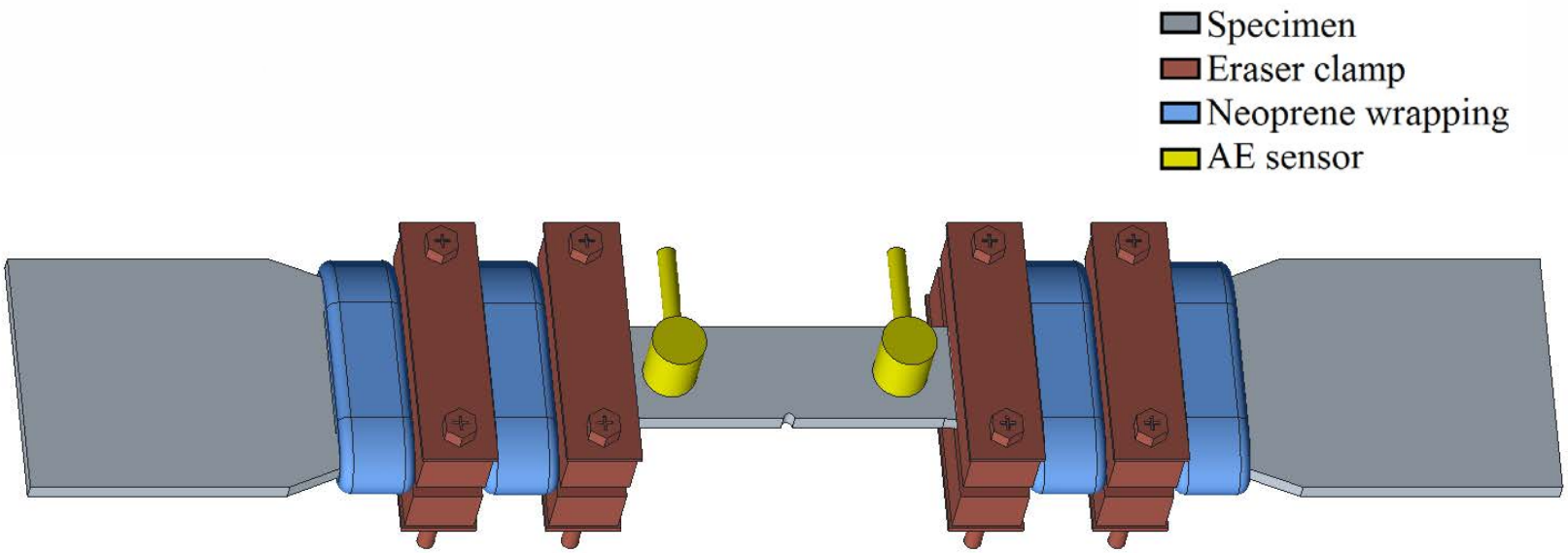
# Denoising Strategies (2/5)

- Mechanical Damping – **Block of grip selection**
  - Compared different gripping blocks of various metals in different configurations
  - The lowest noise level was acquired from 0.190’ thick AA 7075-T6 block.



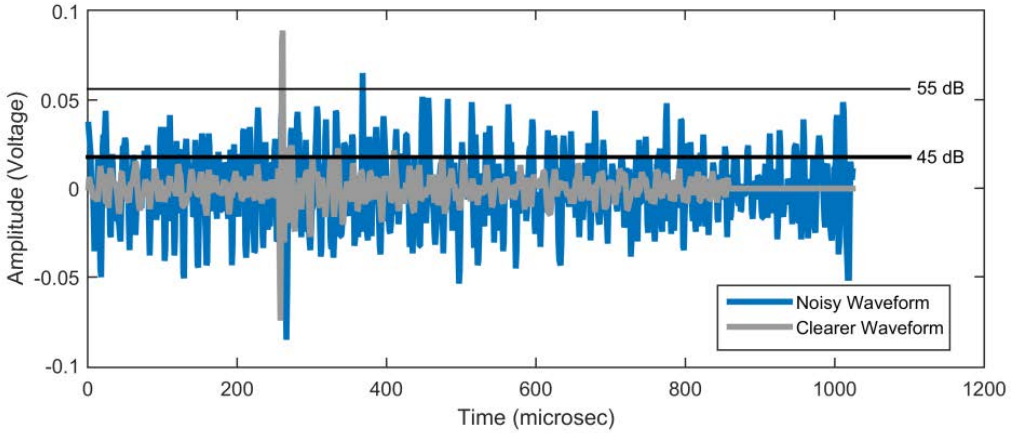
# Denoising Strategies (3/5)

- Mechanical Damping – **Damping material attachment**
  - Added and clamped several damping materials such as rubbers and plastics
  - Iterated through combinations of materials and configurations
  - Best setup is pictured below
  - Decreased noise from 60 – 70 dB to 40 – 50 dB
  - Simple and effective



# Denoising Strategies (4/5)

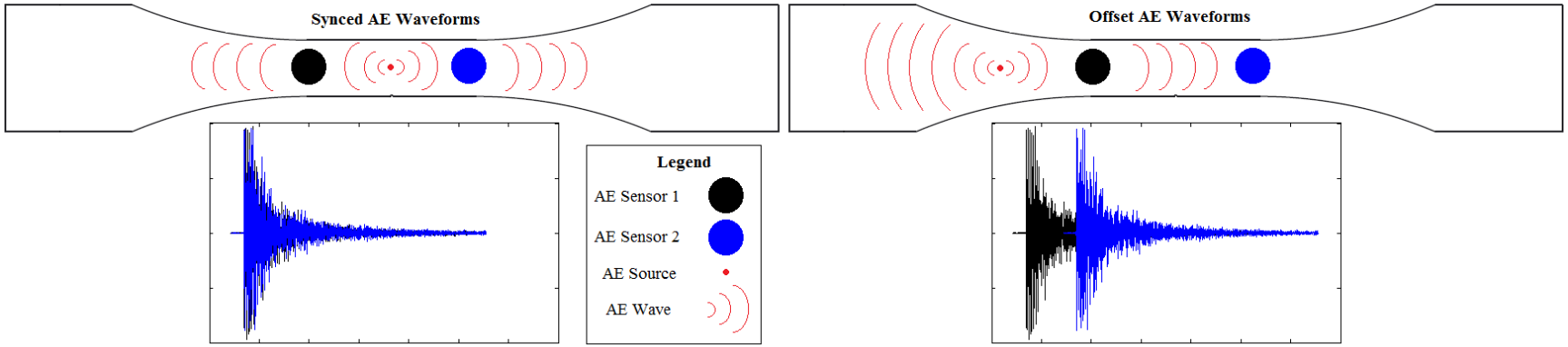
- Software Filtering – **Problems**
  - Cannot filter out noise unless threshold amplitude > noise amplitude
  - AE software system divides signal into waveforms based on first threshold crossing
  - Problem: When AE signal amplitude is *always* > threshold, the acquisition system cannot divide up the signal
  - To collect AE data need to set the threshold > background noise
  - Once this is accomplished, common software filtering methods implemented
  - If threshold < 45 dB, noisy waveform will prevent data from being collected



# Denoising Strategies (5/5)

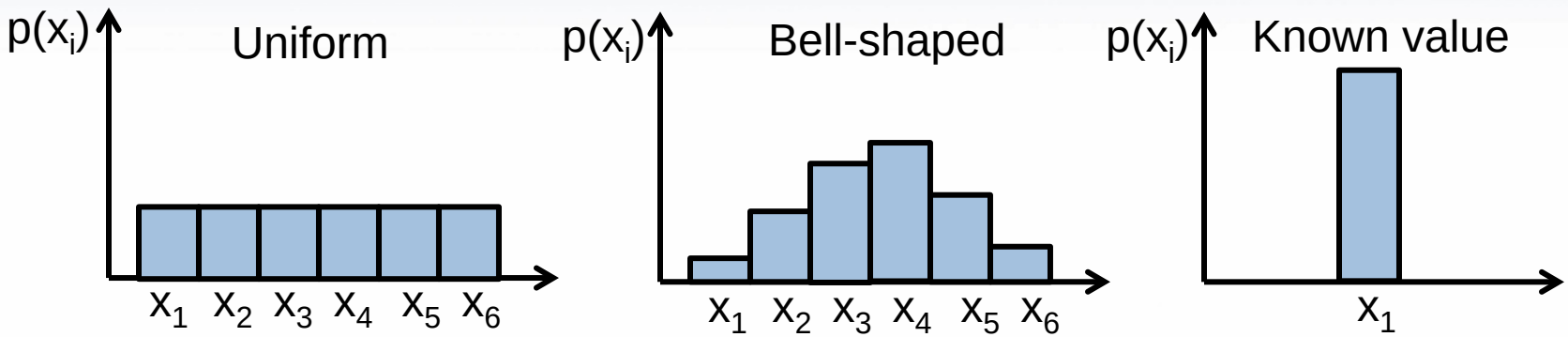
- Software Filtering – **Techniques**
  - Band-pass filter based on frequencies (200 kHz ~ 3 MHz)
  - AE events occurring during loading rather than unloading
  - AE events occurring near peak load
    - Pre-processing with Voltage Time Gate Filter, post-processing with Matlab
  - AE events due to an AE source near the crack
    - Only collect AE events when they reach the two AE sensors at similar times
    - Pre-processing with DeltaT Filter, post-processing with Matlab

DeltaT Filter Diagram



# Entropy Analysis (1/4)

- Information entropy – **Concept**
  - Measurement of surprise about a probability density function




$$Entropy = S = -\sum_{i=1}^{N} p(x_i) \times \log_2(x_i)$$

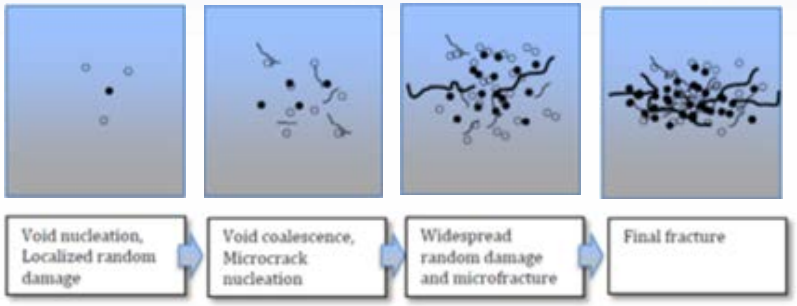
$$\sum_{i=1}^{N} p(x_i) = 1$$

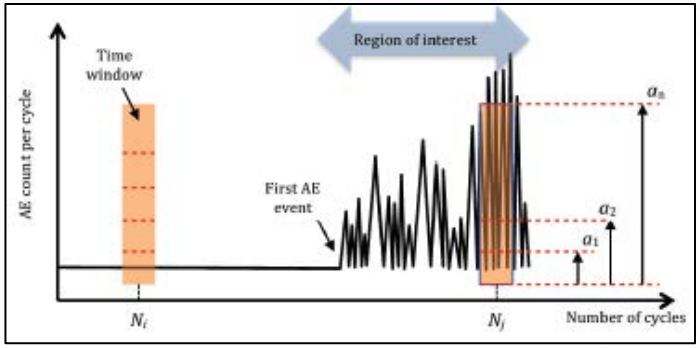
| Distribution | Information Carried | Entropy |
|---|---|---|
| Uniform | Least | S $S_{max}$ |
| Bell-shaped | Some | 0 S $S_{max}$ |
| Known Value | Most | S 0 |

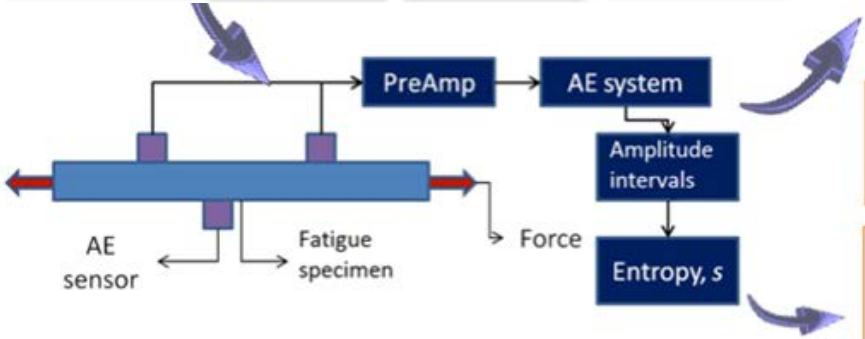
  - Information entropy estimates the randomness from AE signals and correlates well with AE hit count and energy. * Unnthorsson, R., et al., J. Acoustic Emission, 26 (2008), 262–269
  - We investigate information entropy from AE counts as well as AE amplitude distribution and frequency spectrum from individual waveforms.

# Entropy Analysis (2/4)

- Information entropy – **AE counts over <u>multiple</u> AE events**
  - Calculates entropy based on AE events divided between time intervals
  - Entropy evolution correlates well with AE counts evolution




Divide signals into $n$ amplitude intervals:

$a_i \quad i=1,2,\ldots,n$

Define $x_i$ as:

$x_i$ = detected acoustic signals at interval $a_i$

Probability of detecting signals with amplitude $a_i$:

$$p_i = \frac{x_i}{\sum_1^n x_i}$$

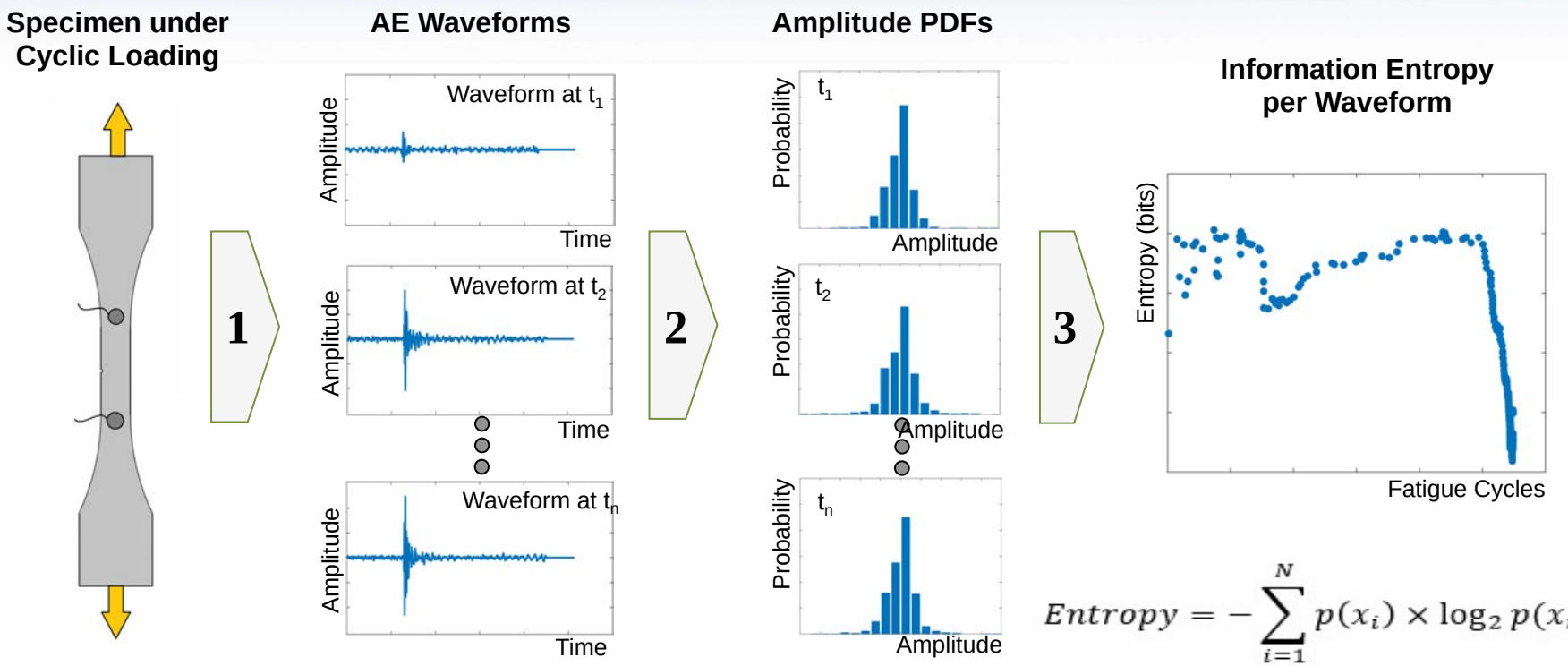
Entropy of the signal, $S$:

$$S = -\sum_1^n p_i \ln p_i$$

* M. Amiri, M. Modarres, E. Lopez Droguett, AE Entropy for Detection of Fatigue Crack Initiation and Growth, prognostics and Health Management (PHM) 2015 IEEE Conference, Austin, TX

# Entropy Analysis (3/4)

- Information entropy – **AE amplitude over <u>individual</u> AE event**
  - Computationally intensive, but improves calculation




$$Entropy = -\sum_{i=1}^{N} p(x_i) \times \log_2 p(x_i)$$

1) AE signals are recorded as the specimen is under fatigue
2) Create normalized histograms which are discrete pdfs
3) Calculate information entropy above where $p(x_i)$ is the pdf of amplitude for each waveform

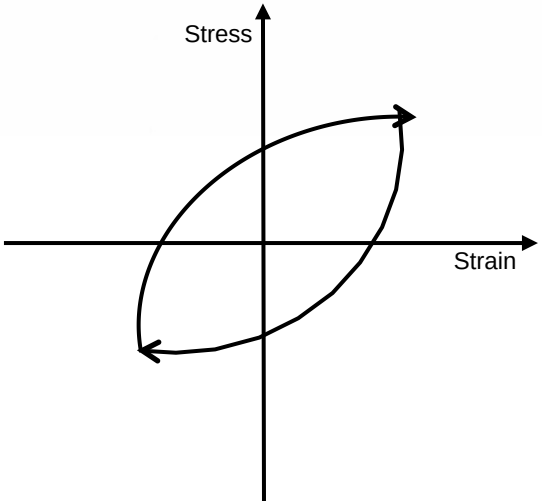
# Entropy Analysis (4/4)

- Thermodynamic entropy
  - Measures of dissipated energy and temperature used
  - The work (dissipated energy) applied in fatigue loading is interpreted by using hysteresis loop from stress-strain plot. (area of closed loop)
  - The material property changes as the load accumulates and the loop shape and temperature changes
  - By this measurement of energy and temperature, internal entropy is computed as

$$\Delta s_i = \sum \frac{(\sigma^* \Delta\varepsilon_p)}{\rho T}$$

  - The entropy and its cumulative value is used in analyzing damage

* T. Temfack and C. Basaran, Materials Science and Technology, (2015), 1-6




A hysteresis loop

# Future Works

- Characterizing damage state (Short-term)
  - Prepared specimens and planned test condition
  - Collect and analyze test data (stress-strain, crack geometry, and AE parameters)
  - Develop model of correlation of AE parameters and damage state
  - Combining AE parameters, temperature gradient and strain energy measurement for a more accurate model

- Applying to STLP (Long-term)
  - Specimen fatigue test according to STLP
  - Suggests novel procedure to detect damage state in large scale with AE

# Publications & Personnel

- Publications (in 2015)
  - Submitted: Effects of Material Variation on Acoustic Emissions-Based, Large-Crack Growth Model, Christine Sauerbrunn, Mohammad Modarres
  - Acoustic Emission Entropy as a Measure of Damage in Materials, Ali Kahirdeh, Christine Sauerbrunn, Mohammad Modarres, Proceedings of the 35th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, MaxEnt-2015, Potsdam, NY, 2015
  - Small Fatigue Crack Initiation and Sizing Using Acoustic Emission, A. Keshtgar, M. Modarres, The annual Meeting of the Society for the Advancement of Material and Process Engineering, SAMPE2015, Baltimore, MD, May 18-21, 2015

- Personnel
  - Post-Doc: Ali Kahirdeh
  - Grad-Students: Christine Sauerbrunn and Huisung Yun

# Question & Answer

<https://www.fluentstream.com/5-questions-to-ask/, 5/23/13>