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

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INTRODUCTION

Motivation

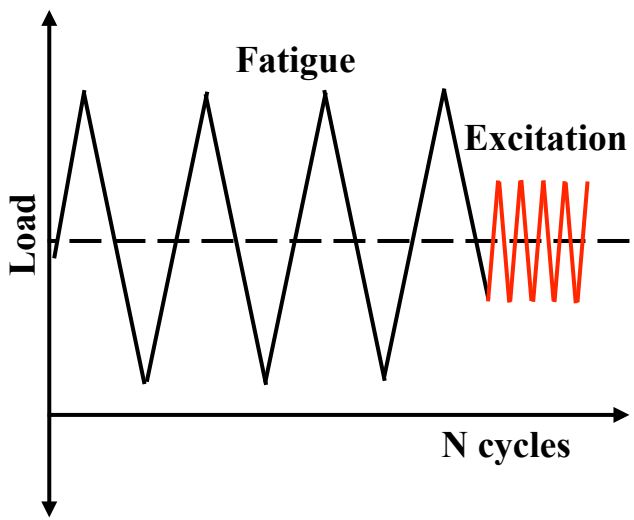
- Full-scale fatigue testing and safe-life methodology is employed to estimate aircraft fatigue life
  - Time demanding, expensive, and often leads to premature aircraft retirement[1]
- Nondestructive evaluation methods supplement service life models[2]
- Previous work has correlated acoustic emission (AE) signals to large crack growth[3-12]

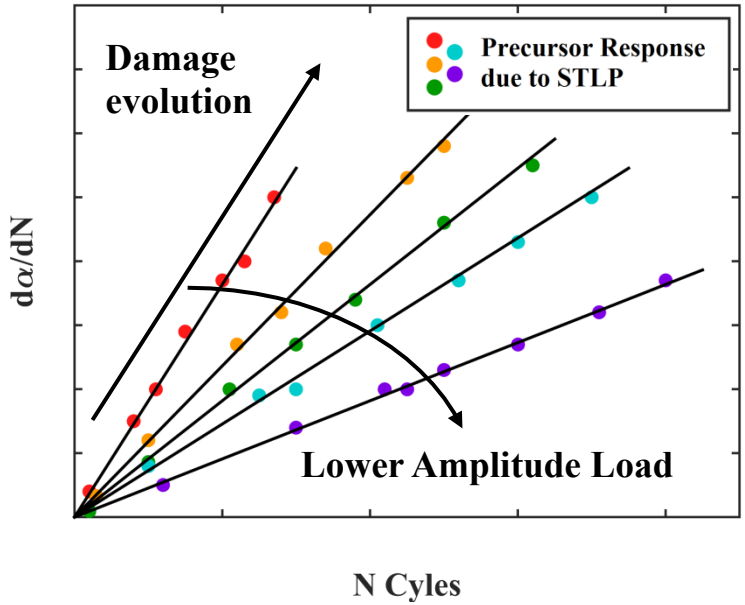
Objective

- Estimate remaining useful life (RUL) based on behavior of identified damage precursors in AE signals
  - Identify potential damage precursors in AE signals and correlate to fatigue damage both prior to and after a visible crack has initiated
  - Observe behaviors of damage precursors during excitation loading or small vibrations

SCOPE OF RESEARCH

- Stage 1 (current) – Identify damage precursors attributed to microcracks prior to visible damage
- Stage 2 (future) – Observe behaviors of damage precursors during short-term, high-frequency, excitation loading





STLP = Short-term loading procedure = excitation loading

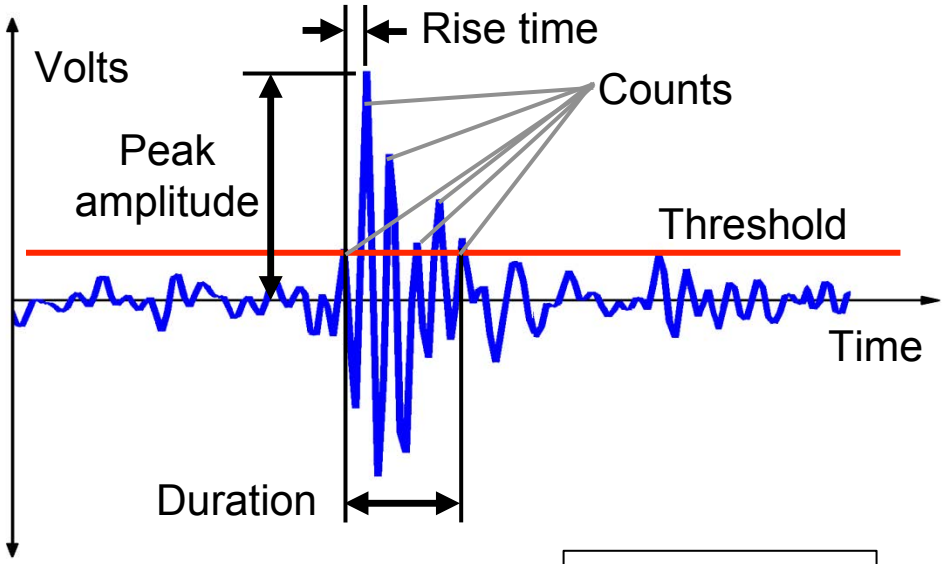
COMPLETED WORK – STAGE 1

- Performed fatigue experiments with AL7075-T6
- Recorded AE signals, measured strain, and monitored crack initiation and growth during experiments
- Developed three methods to estimate information entropy from AE signals as a potentially more sensitive AE metric
- Used modulus degradation as the “true” measure of fatigue damage rather than crack length

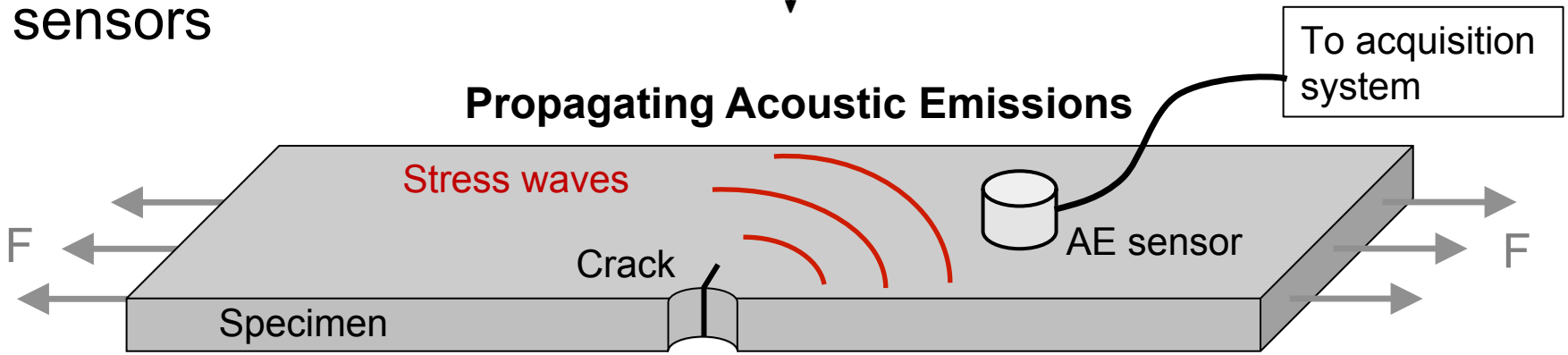
ACOUSTIC EMISSIONS

- Acoustic emissions = stress waves that propagate when an applied load causes permanent deformation and stored elastic strain energy is released[13]
- Detected with piezoelectric sensors

Example of AE Waveform

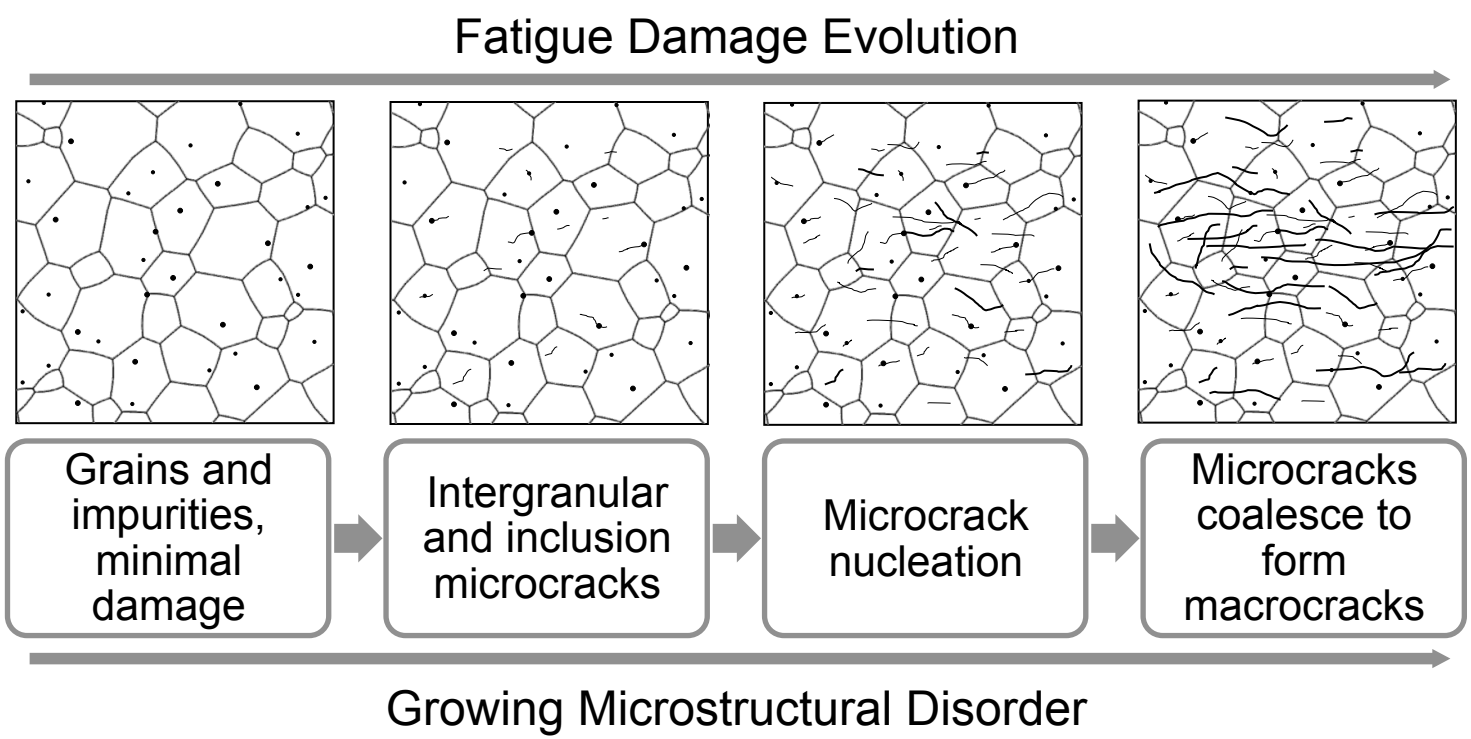


Propagating Acoustic Emissions



MICROSTRUCTURAL DISORDER

- AE signals are emitted due to dislocation movement and microcracks[10-11, 14-23]
- AE features correlated to damage, but one can use a more proper and sensitive measure of disorder in AE signals: Information entropy



INFORMATION ENTROPY

- Information entropy: measure of disorder or uncertainty in a message[24, 25]

- Given a probability distribution, it is possible to express information entropy of this distribution as[26]

$$H = -\sum_{i=1}^{n} p(x_i) \log_2 p(x_i)$$

  - $p(x_i)$ is the probability a certain value, x_i, present within the message with n possible values, units are in bits
  - Need $\sum_{i=1}^{n} p(x_i) = 1$

Information Entropy: Acoustic Emission As a Damage Signal

Discrete approaches

Acoustic emission waveforms

↓

Histogram of the AE signals

↓

Calculation of p_i each waveform

↓

Probability distribution (p_i)

↓

Shannon Entropy

$$S_E = -\sum_{i=1}^{n} p_i \log_2 (p_i)$$

Parametric approach

Acoustic emission waveforms

↓

Assigning a set of trial probability density function to the acoustic waveform

↓

Model selection based on the Maximum Entropy obtained

↓

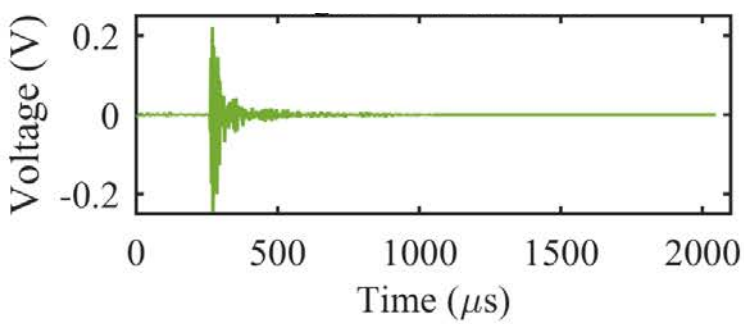
Shannon Entropy

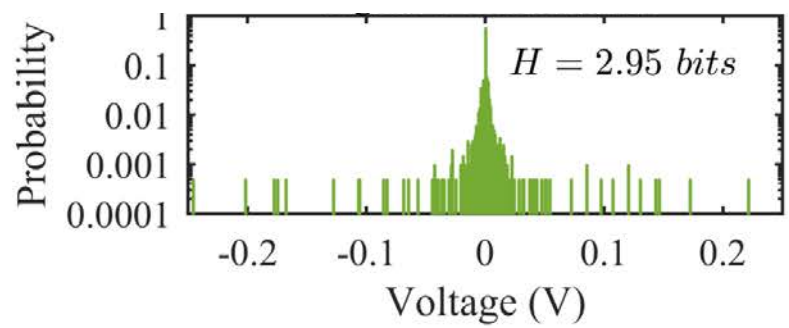
$$S = -\int_{-\infty}^{+\infty} f(x) \log[f(x)]\, dx$$

INFORMATION ENTROPY APPLIED TO AE

- One could express information entropy from AE amplitude[27, 28], frequency[27], and count[29, 30] distributions from several AE signals
- Instead of using summary AE features like amplitude and counts, information entropy from each individual AE signal can be calculated
- We proposed three formulations:
  1. instantaneous entropy
  2. average entropy
  3. weighted average entropy

$$H = -\sum_{i=1}^{n} p(x_i) \log_2 p(x_i)$$





Other Entropic Damage Characterizations

Entropy for damage characterization

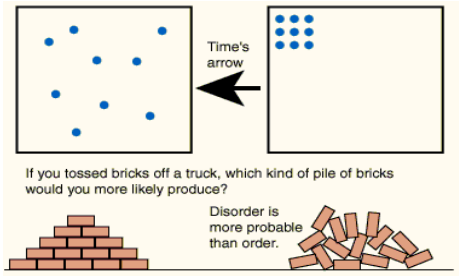
Entropy $S = K_B \ln W$ Damage

Statistical mechanics microscopic interpretation

- Basaran et al. (1998, 2002, 2004, 2007)
- Tucker et al. (2012)
- Chen et al. (2012)
- Temfeck et al. (2015)

Macroscopic interpretation within the second law of thermodynamics

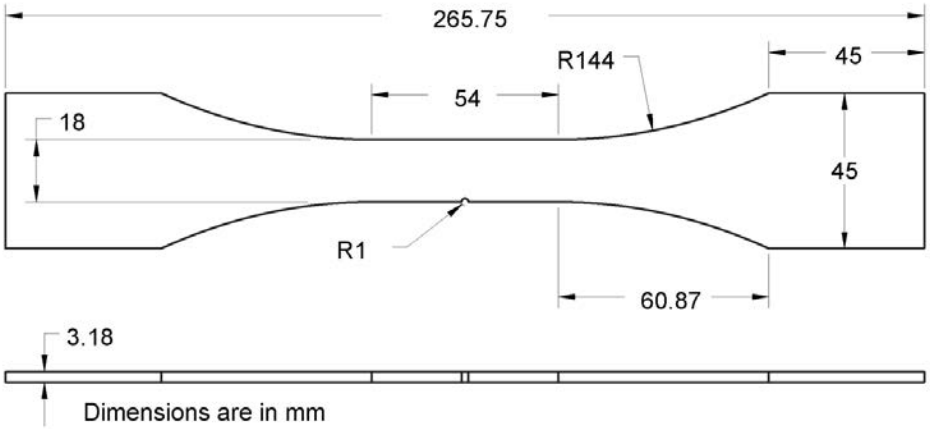
- Feinberg and Widom (1996, 2000)
- Bryant et al.(2008)
- Amiri and Modarres(2013)
- Imanian and Modarres (2015)



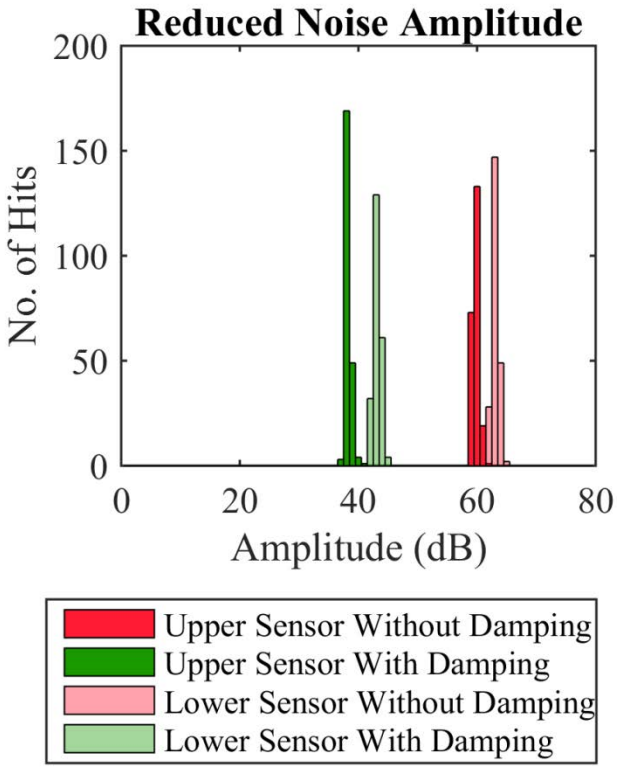
EXPERIMENTAL PROCEDURE

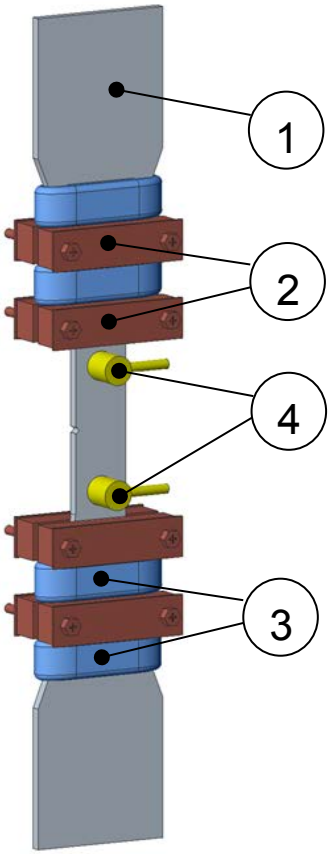
Number of tests	26, reduced analysis to 8
Material	Al 7075-T6
Loading ratio	0.1
Loading freq.	5 Hz
Applied load	8-15 kN
Strain measurement	Epsilon 3542 extensometer with 25 mm gauge length
Crack monitoring system	Optical microscope, images taken every 5 seconds
AE sensors	Two resonant Micro30s sensors from MISTRAS Group, 150-400 kHz range, resonant freq. of 225 kHz
AE background noise reduction	Mechanical damping apparatus, post-process filtering

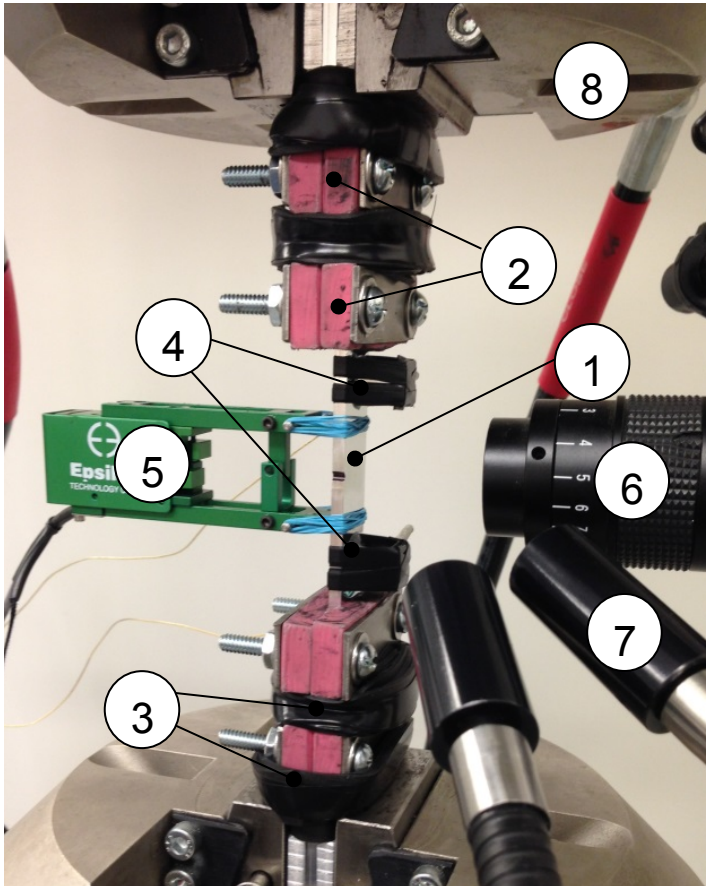
AE Parameter	Value
Peak definition time (PDT)	300 μs
Hit definition time (HDT)	600 μs
Hit lockout time (HLT)	1000 μs
Sampling rate	1 MSPS
Pre-trigger length	256 μs
Hit length	2048 μs
Band pass filter	1 kHz-3 MHz



MECHANICAL DAMPING





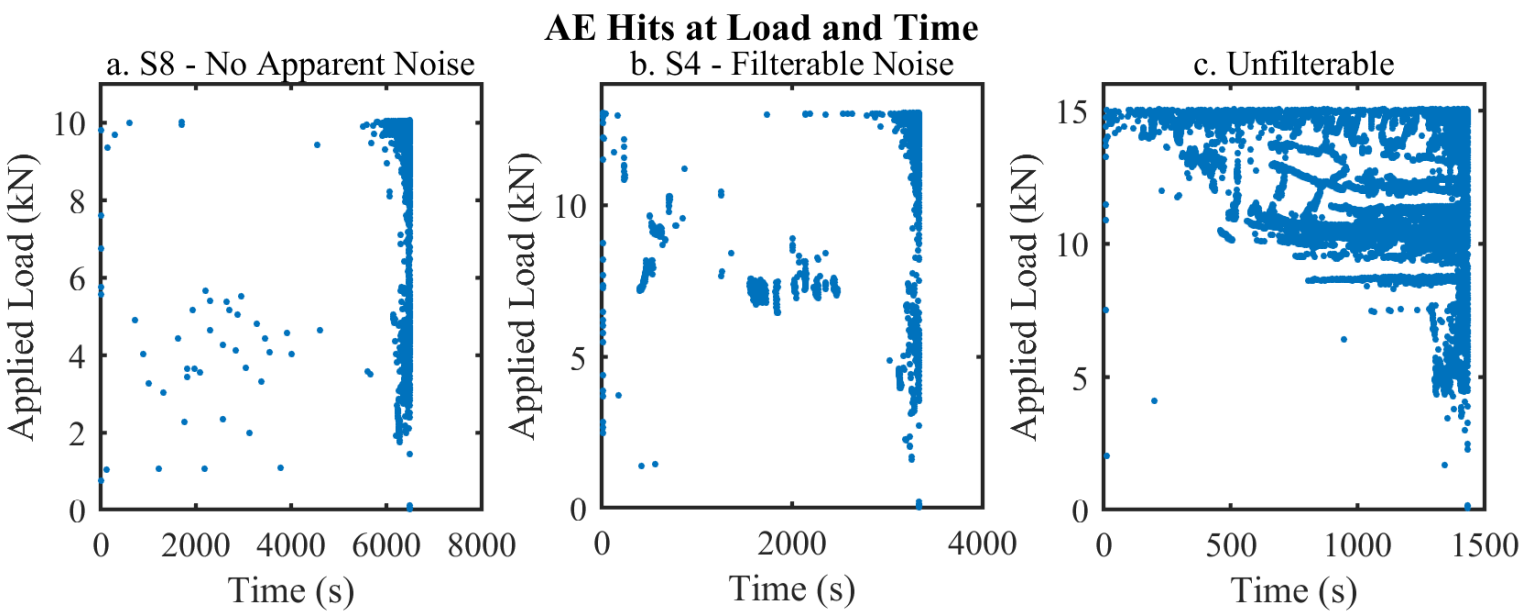


Reduced noise to below 45 dB

1. Specimen
2. Clamped styrene-butadiene rubber
3. Wrapped neoprene strip
4. Acoustic sensor
5. Extensometer
6. Optical microscope
7. External light source
8. Testing grip

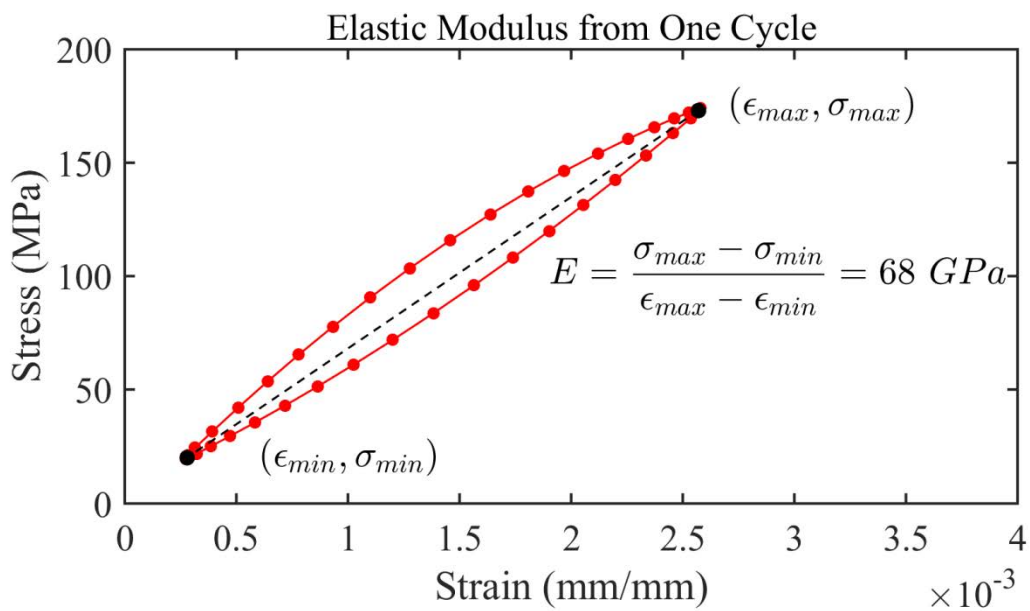
POST-PROCESSING FILTERING

- Expected AE signal behavior
  - Sporadic signal at various loads throughout fatigue life
  - After crack initiation, many signals at high loads and then at all loads
- Assume clusters of signals at low/mid loads are noise



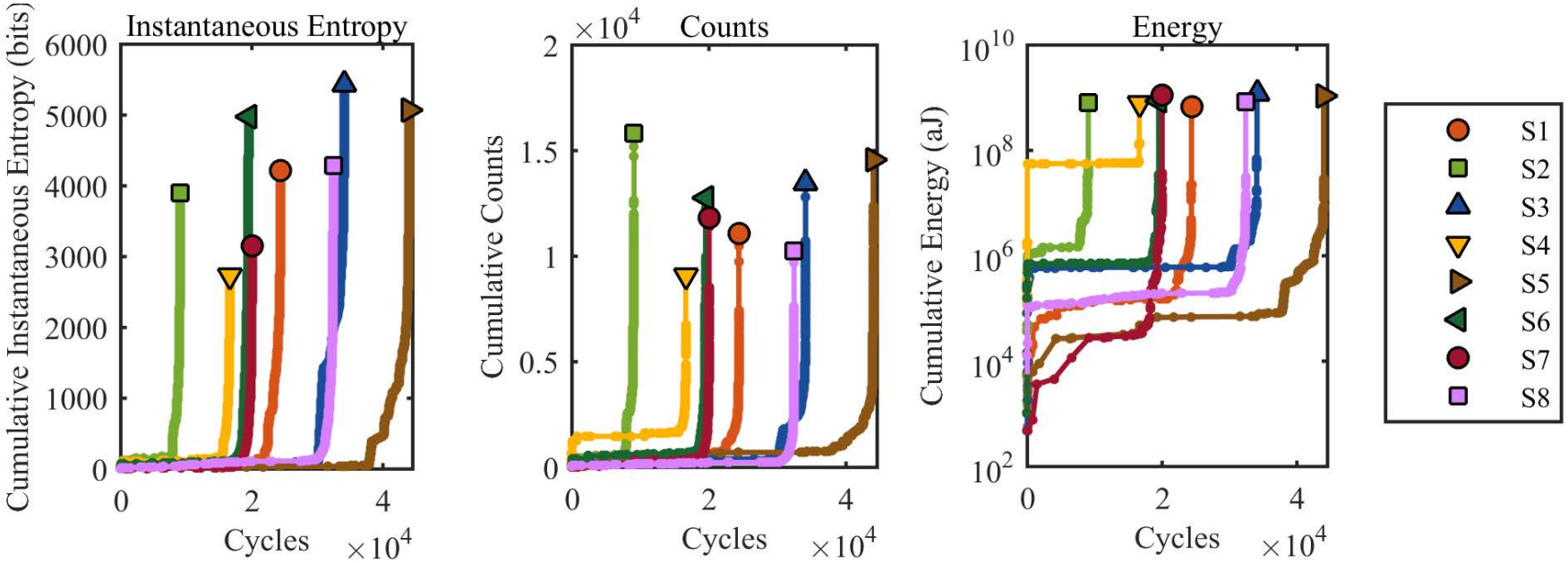
ELASTIC MODULUS DEGRADATION

- Wish to estimate damage prior to an observable crack
- Assume that structural degradation is reflected as a decrease in elastic modulus
- Normalize modulus to compare trends between tests to yield *modulus degradation damage (MDD)*
- $MDD = E_{instant} - E$
  - 0 is a pristine specimen
  - 1 is a fractured specimen



CYCLIC TRENDS OF CUMULATIVE AE PARAMETERS

- Can compare the cyclic trends of cumulative *instantaneous entropy*, cumulative counts, and cumulative absolute energy



- Trends prove to be similar to fatigue stages

VARIATION IN FINAL VALUES AT FRACTURE

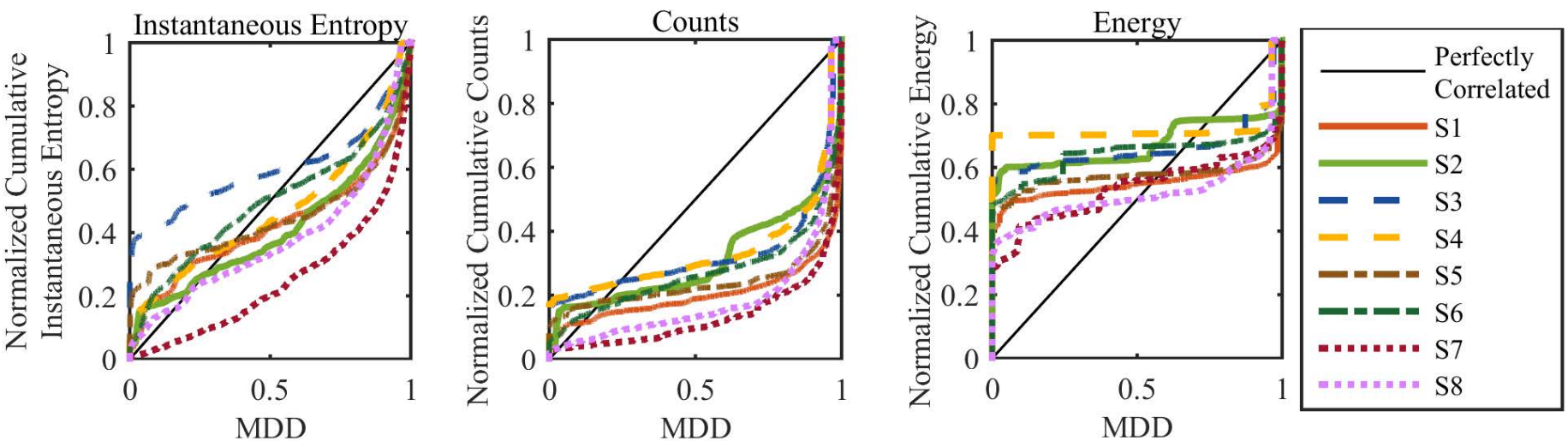
- Final values at specimen fracture are comparable but vary
  - Measure variance with coefficient of variation, $\%CV = \sigma/\mu * 100\%$

Cumulative AE Parameter	Mean (μ)	Standard Deviation (σ)	Coefficient of Variation (CV)
Instantaneous entropy	4221.6 bits	945.2 bits	22.4%
Counts	12,360	2,245	18.2%
Energy	9.21×10^8 aJ	1.87×10^8 aJ	20.2%

- Instantaneous entropy has highest variation
  - More sensitive to slight differences in AE signals
  - **Could potentially be a better, more sensitive measure of damage if variations between experiments were reduced**

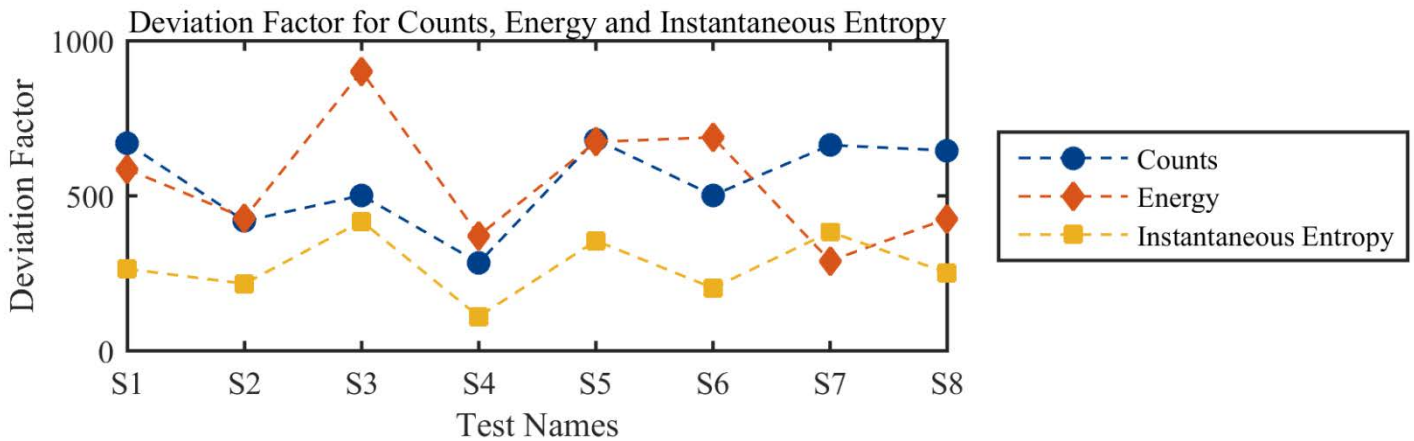
DAMAGE TRENDS OF CUMULATIVE AE PARAMETERS

- Want to assess how AE parameters correlate to fatigue damage
  - Normalize AE parameters: $p_{norm} = p_i - p_{min} / p_{max} - p_{min}$ where *p* is any AE parameter
- Assumption: normalized cumulative AE parameters with a one-to-one relationship with measured damage suggest "perfect correlation"



DAMAGE TRENDS OF CUMULATIVE AE PARAMETERS

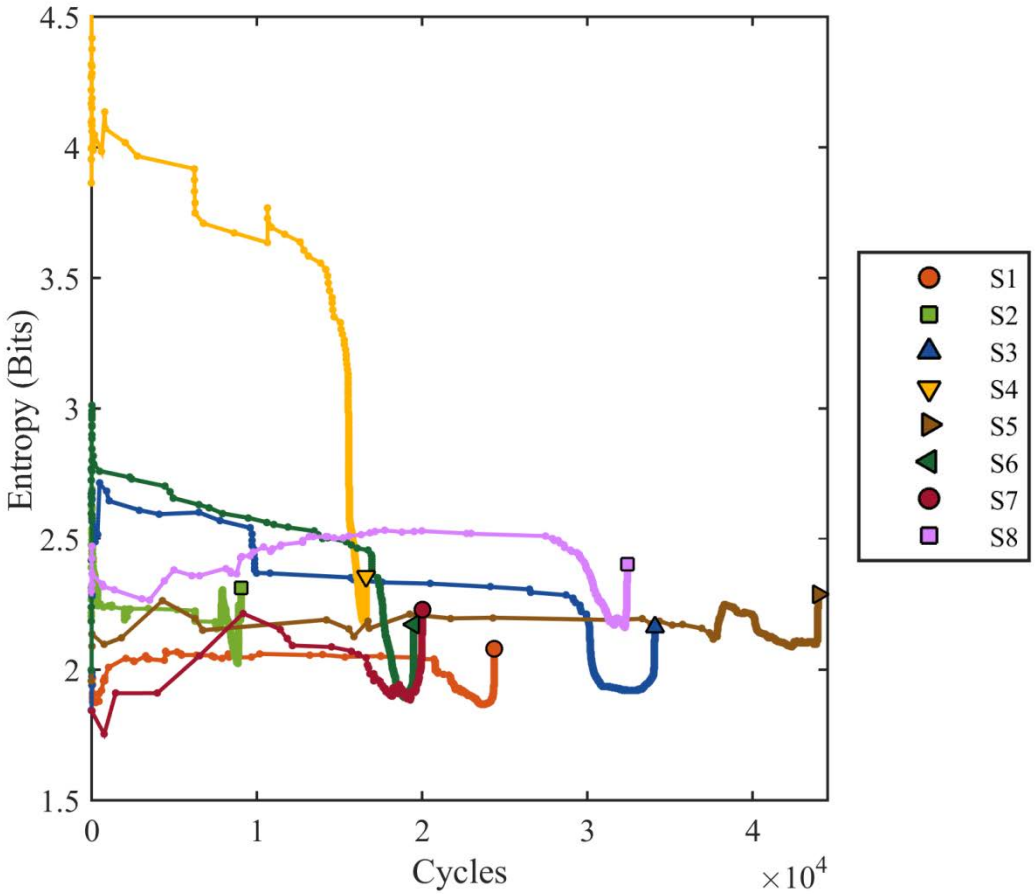
- *Deviation factor* = summation of deviations at each AE signal between cumulative trends and one-to-one model
- AE parameter with lowest deviation factor is assumed to be a better representation of damage



- **Feature entropy may be a better statistic of measure damage compared to counts and energy**
  - Lowest deviation factor for all but one experiment

CYCLIC TREND OF AVERAGE ENTROPY

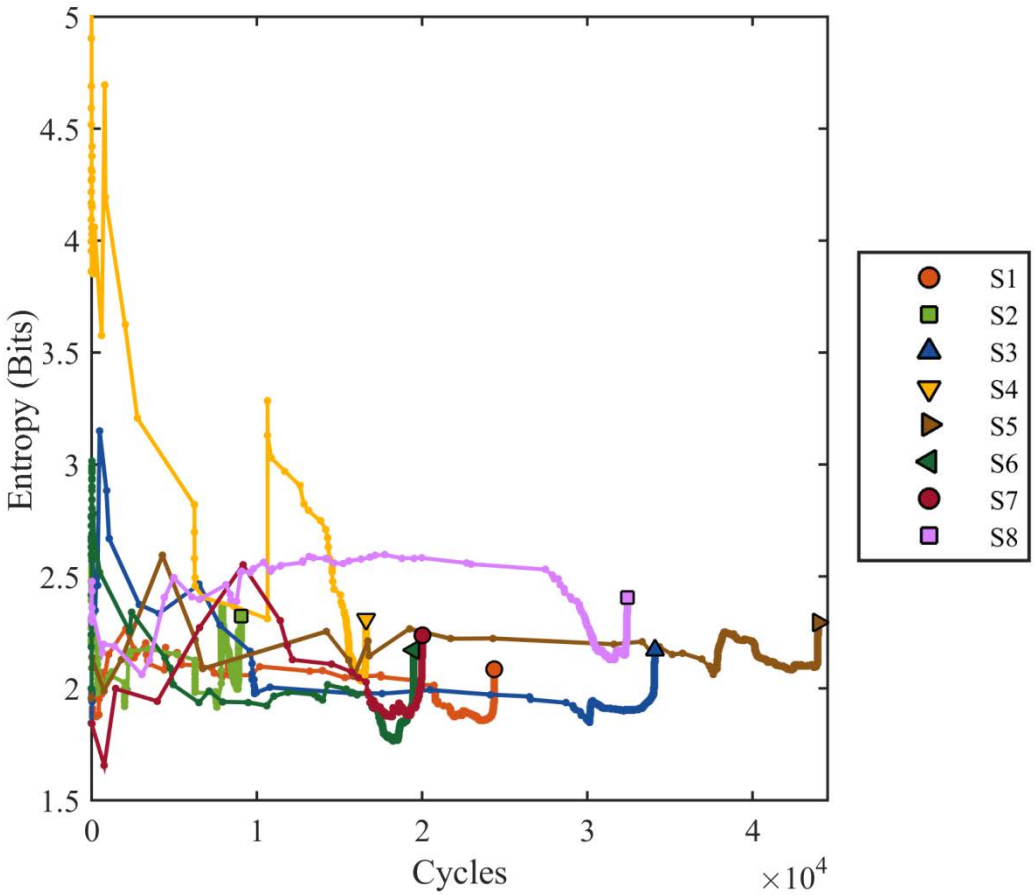
Initiation => 0.25 mm => 1mm => Fracture



- Varies for the first few signals, voltage distribution not yet inertial
- Sporadic AE signals are received for the majority of life
- As crack initiates, entropy decreases meaning signals have consistent and low disorder
- High disorder signals just before fracture
- **May be used to differentiate between small and large cracks**

TREND OF WEIGHTED AVERAGE ENTROPY

Initiation => 0.25 mm => 1mm => Fracture



- Same trend as instantaneous entropy, but more erratic
- **May also be used to differentiate between small and large cracks**

ACCOMPLISHMENTS

- Three proposed methods to estimate the disorder from AE signals proved to be unique and informative
  - Found that instantaneous entropy may better correlate with the fatigue damage than the AE counts and energy
  - Found that average and weighted average entropy methods may be able to differentiate between small and large cracks
- AE noise was reduced by means of a mechanical damping apparatus and post-process noise reduction techniques
- Use of modulus degradation as a measure of damage prior to a crack was investigated
- Recommended instantaneous entropy as well as all other AE parameters in future stage of excitation testing

ISSUES

- AE noise amplitude was too high => reduced by applying mechanical damping
- Still received noise signals after damping => filtered noise using post processing methods
- Uncertain and inconsistent MDD at supposedly consistent crack lengths
  - Due to monitoring and measuring crack on one side of specimen and uneven crack propagation
  - Will consider making specimen thicker to reduce uneven propagation, monitoring crack from different view, measuring strain with a more sensitive method

FUTURE WORK

- Quantitatively define relationship between information entropy and modulus degradation damage
- Investigate thermodynamic entropy as additional potential damage precursors
- Finalize Stage 2 of the research where potential damage precursors will be monitored during excitation loading in variously degraded structures
  - Design test setup that will simultaneously collect all damage precursor data
  - Select best form of the high frequency excitation conditions to elicit damage precursors while not causing further fatigue damage
  - Assess feasibility and value of STLP as an applied NDE technique

RECENT PUBLICATIONS AND PRESENTATIONS

- Journal papers
  - Kahirdeh A, Sauerbrunn C, Yun H, Modarres M (2016) A parametric approach to estimation of the acoustic entropy during the fatigue phenomenon. International Journal of Fatigue, under review
  - Sauerbrunn C, Kahirdeh A, Yun H, Modarres M (2016) Damage assessment using information entropy of individual acoustic emission waveforms during cyclic fatigue loading. International Journal of Fracture, submitted manuscript
- Thesis
  - Sauerbrunn C (2016) Evaluating information entropy from acoustic emission waveforms as a fatigue damage metric for Al7075-T6. M.S. thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD

RECENT PUBLICATIONS AND PRESENTATIONS

- Conference papers and presentations
  - Kahirdeh A, Sauerbrunn C, Modarres M (2015) Acoustic emission entropy as a measure of damage in materials. 35th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, Potsdam, NY
  - Sauerbrunn C, Modarres M (2015) Effects of material variation on acoustic emissions-based, large-crack growth model. 5th American Society for Nondestructive Testing Spring Research Symposium, New Orleans, LA
  - Sauerbrunn C, Modarres M (2016) Estimating fatigue damage with acoustic emission entropy prior to a visible crack. Nondestructive Evaluation of Aerospace Materials and Structure, St. Louis, MO
  - Kahirdeh A, Sauerbrunn C, Yun H, Modarres M (2016) Can energy dissipation and entropy production characterize damage evolution in loaded solid materials? 36th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, Ghent, Belgium

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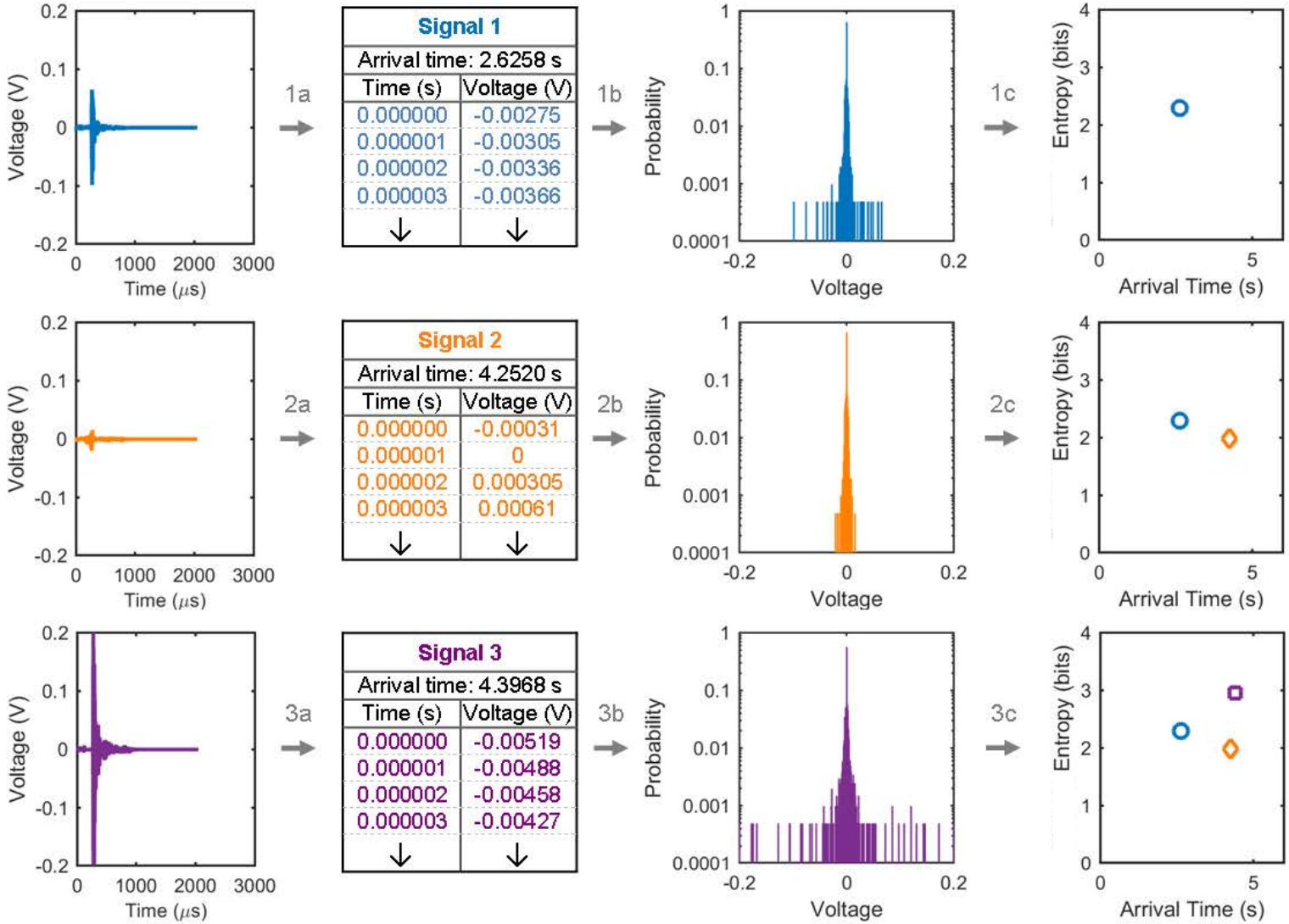
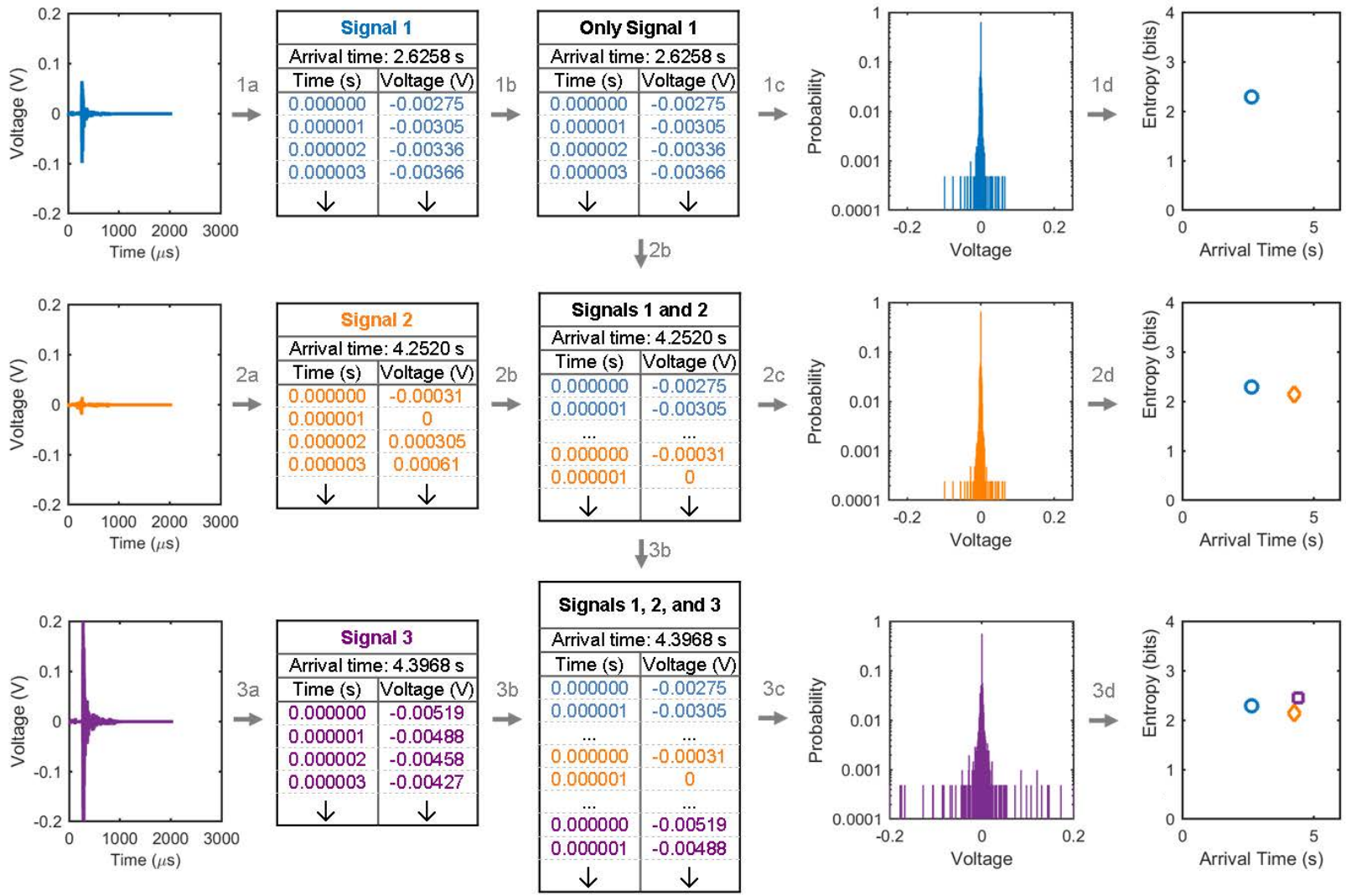
FURTHUR INFOMATION

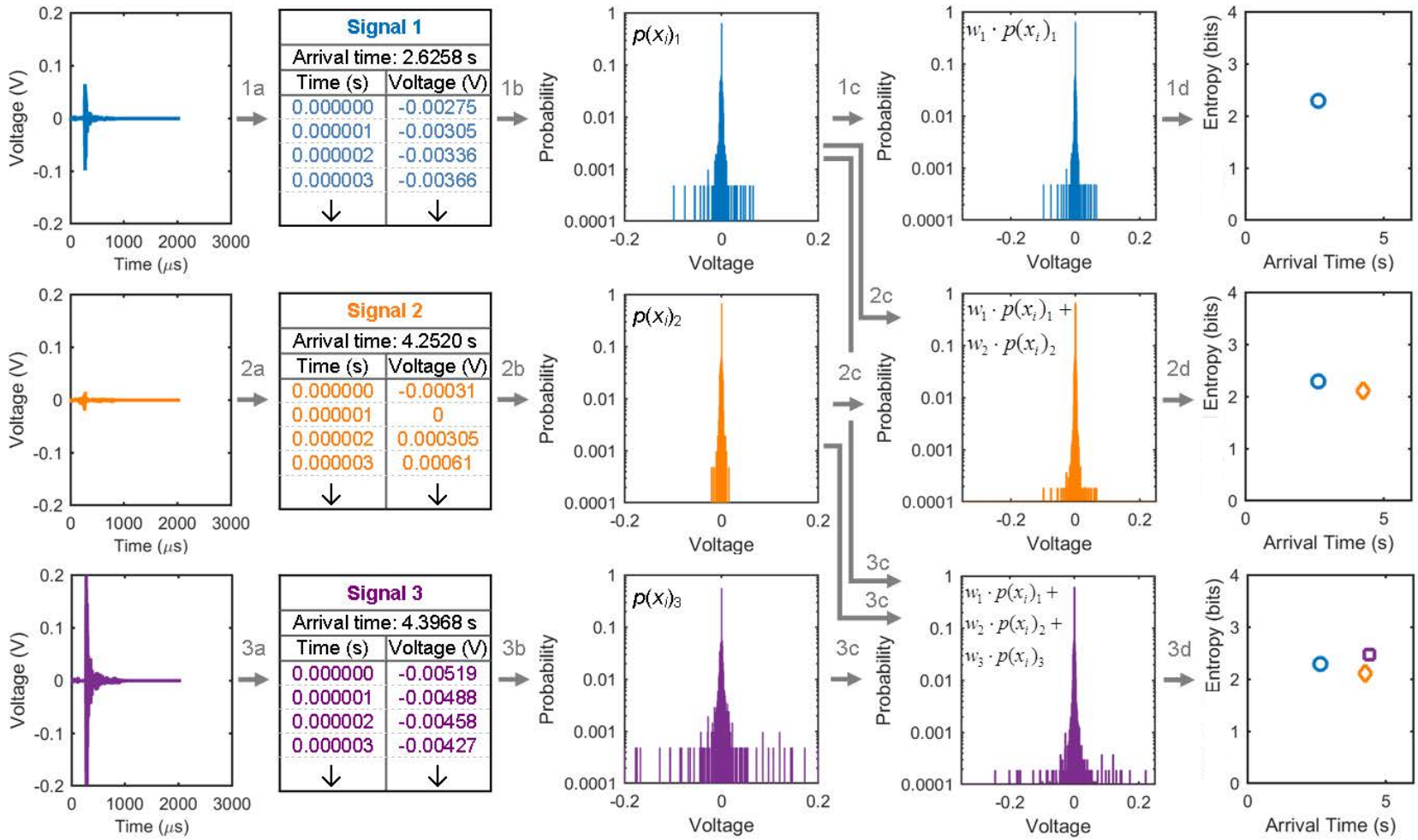
INSTANTANEOUS ENTROPY



AVERAGE ENTROPY



WEIGHTED AVERAGE ENTROPY



$$\vec{w} = \frac{\overrightarrow{AT}}{\sum_{i=1}^{n} AT_i} \qquad Ex\text{:}\ [w_1 \quad w_2 \quad w_3] = \frac{[AT_1 \quad AT_2 \quad AT_3]}{AT_1 + AT_2 + AT_3}$$

SUMMARY OF ENTROPY FORMULATIONS

Entropy Formulation	Assumption about "true" AE voltage distribution	How best to estimate "true" AE voltage distribution	Behavior with increasing fatigue damage
Instantaneous entropy	Ever-changing and independent between time steps	Independent distributions from each received AE signal	Erratic since all values are independent
Average entropy	Slowly changing where changes are assumed to occur with received AE signals	Combine all received AE signal distributions such that all signals have equal weight on estimate	Inertial since values are dependent on all received voltage readings
Weighted average entropy	Slowly changing where changes are assumed to occur throughout fatigue life	Combine received AE signal distributions such that recent signals have more weight on the estimate than previous signals	Inertial yet slightly erratic since values are dependent on all voltage readings but influenced more by current signals

POST-PROCESSING FILTERING

- Despite mechanical damping, still collected AE signals believed to be background noise
- Filter based on the applied load at the point of the received signals[3, 9, 11, 20]