Instrumentation and Sensors: Acoustics

March 6, 2024

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Motivation

Development of acoustic monitoring techniques that can be coupled with embedded fiber-optic sensors for in-situ structural monitoring of inaccessible microreactor components

FY24 Goals

Integrate acoustic processing methods, analytical techniques, and new experimental data for defect location information and other metrics

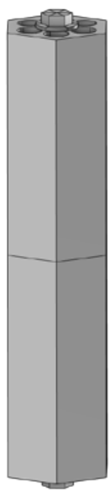
- Evaluate methods of machine learning, FEA modeling, and analysis using prior demonstration data for defect location information and other metrics
- Integrate with ORNL optical sensing development to incorporate technology capabilities & limitations into our modeling and experimental designs

Can we leverage resonance from ambient vibrations to monitor for structural changes?

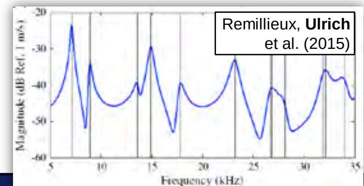
Experiment

Acoustic testing of stressed core-block proxy

intact and damaged



Methods

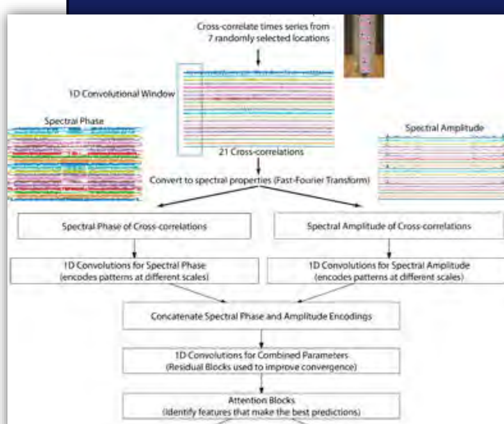


Resonant Ultrasound Spectroscopy

linear & nonlinear

Machine Learning

neural networks (NN)



Outcomes

Elastic material properties

Identify variations in stress & damage states

Inform future embedded sensing designs

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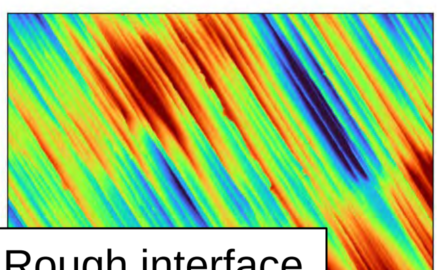
Demonstration test matrix and operational relevance

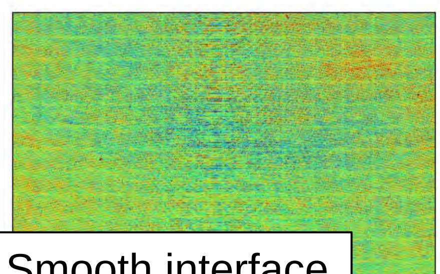
105 scan points
6 stress states
3 damage states

Monitoring Setting

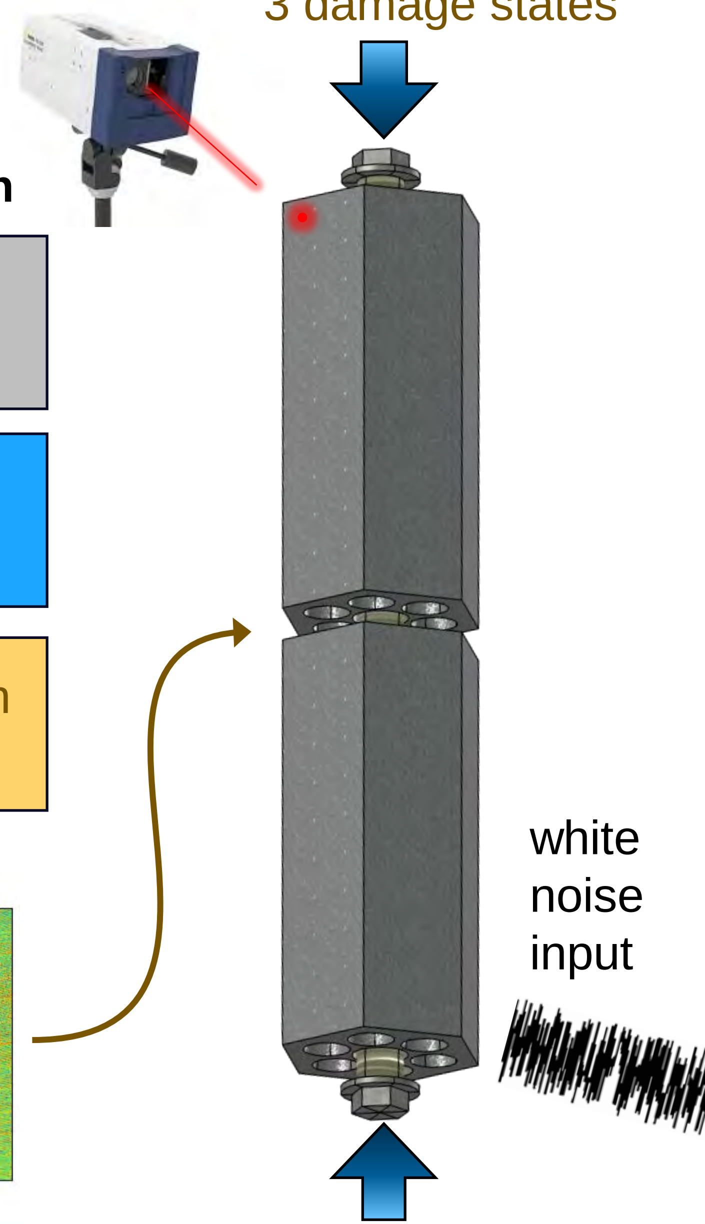
		Operational	**Demonstration**
Measure		embedded fiber optics (ORNL)	laser Doppler vibrometer
Component status	**Stress**	thermal gradients	mechanical compression
	Damage	joint failure, embrittlement, etc.	joint created in test article



Rough interface



Smooth interface

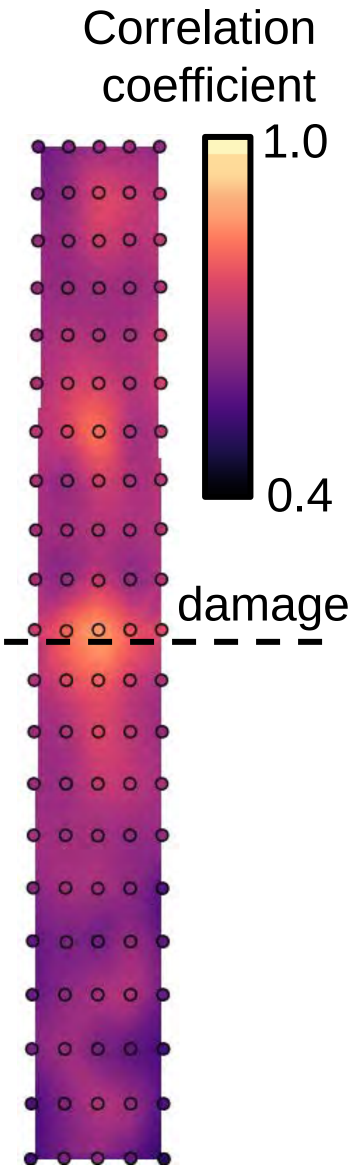


Damage identification and localization

Basic damage identification demonstrated in FY23

Graph neural network (GNN) currently being tested against convolutional neural network

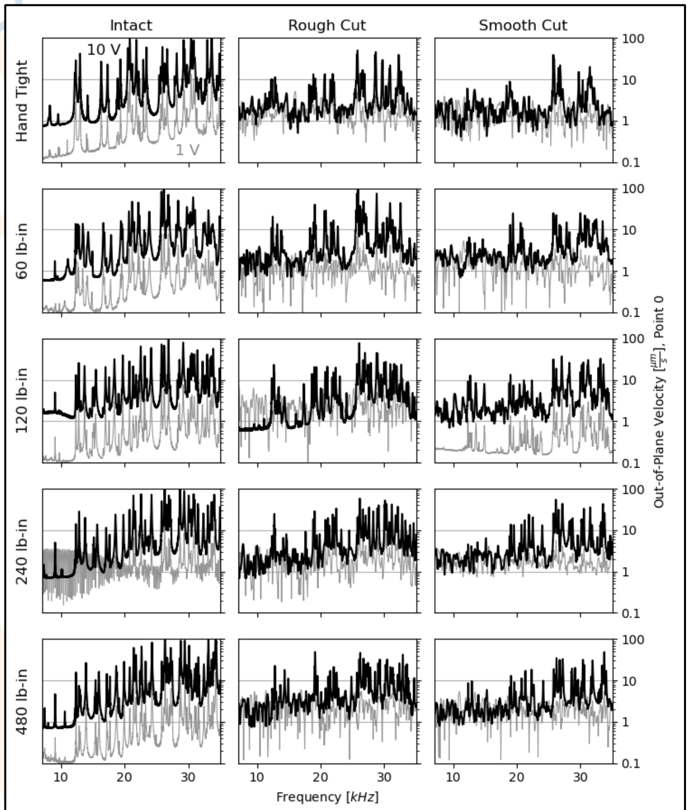
- Target outputs: Component state of health and damage location from existing vibrational dataset
- Current priority: develop optimization scheme to identify a reduced set of stations without sacrificing prediction power
  - To mimic current & expected limitations of ORNL embedded sensing technology

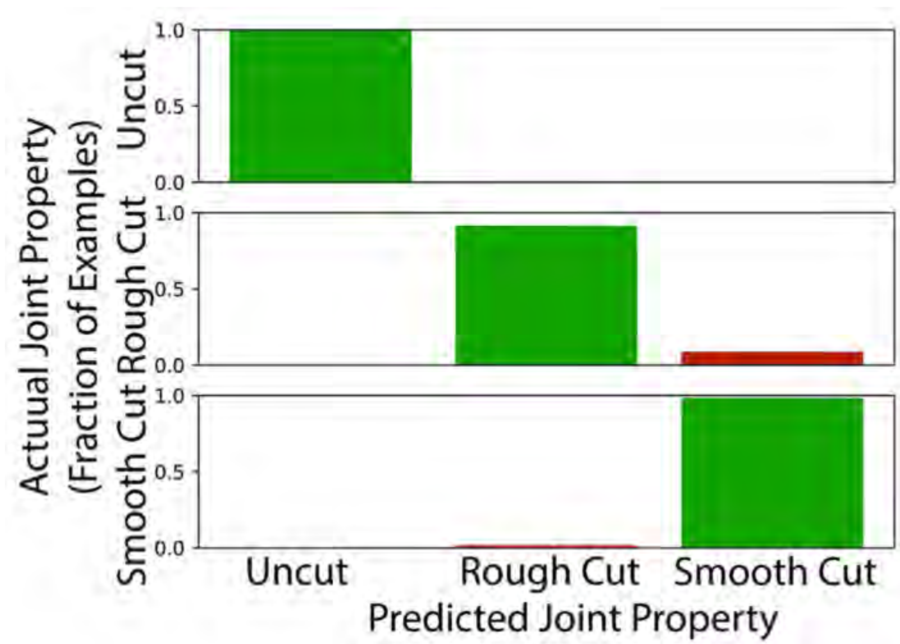


Convolutional NN predictions of damage state:

100% correct identification of presence of joint

94% correct prediction of joint roughness





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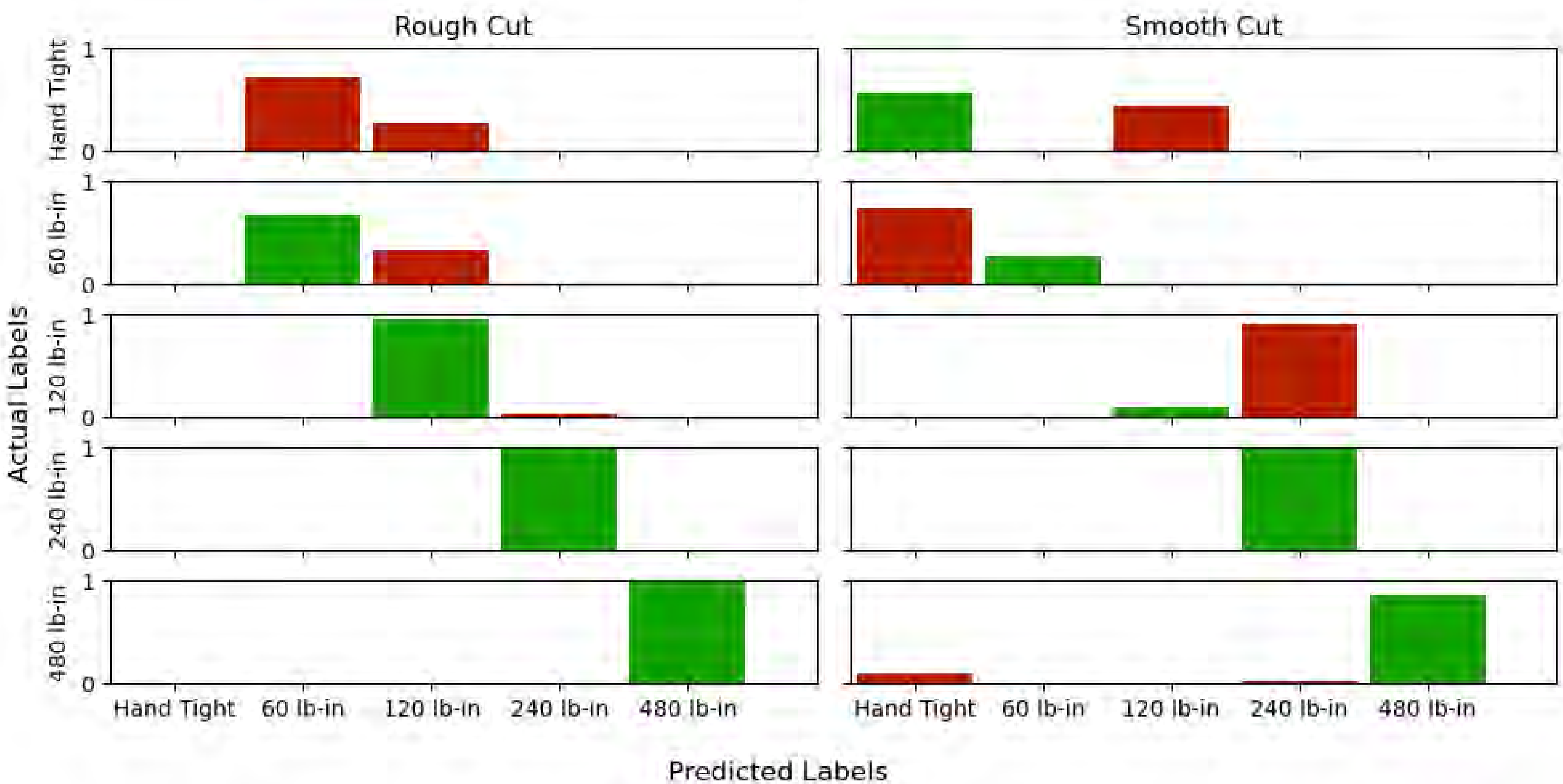
Predictions of combined stress & damage states:

75% accurate for rough cut, 60% for smooth cut

Improved accuracy at higher stress levels



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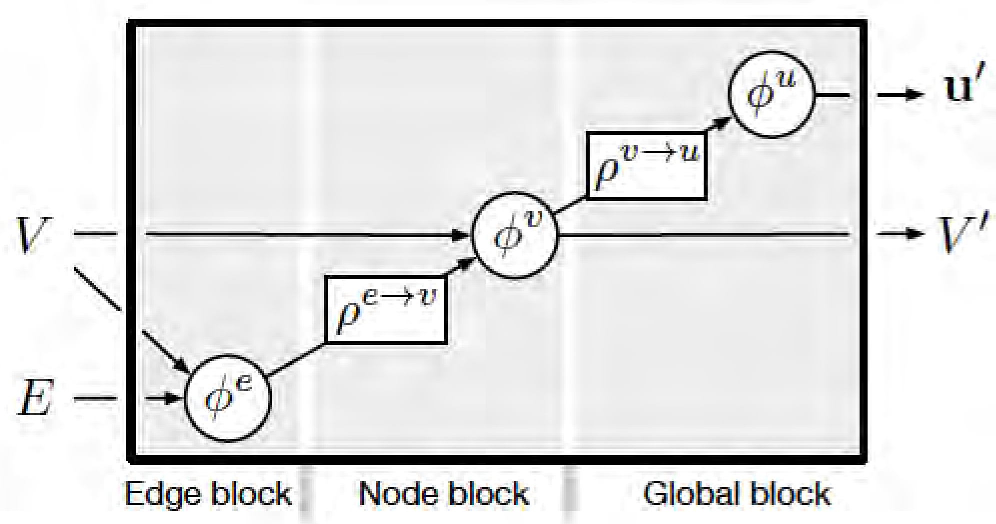
Graph neural networks

- Nodes & edges connect features of importance, similar to physical experiment design
- Expected behavior: the most important edges & subgraphs will correlate with damage location



V = Station Information (time series recorded at each station)

E = Interstation Relationships (cross-correlations)

u = Universal Properties (strain, damage state, etc.)

Battaglia et al. (2018, October 17). Relational inductive biases, deep learning, and graph networks. arXiv. Retrieved from http://arxiv.org/abs/1806.01261

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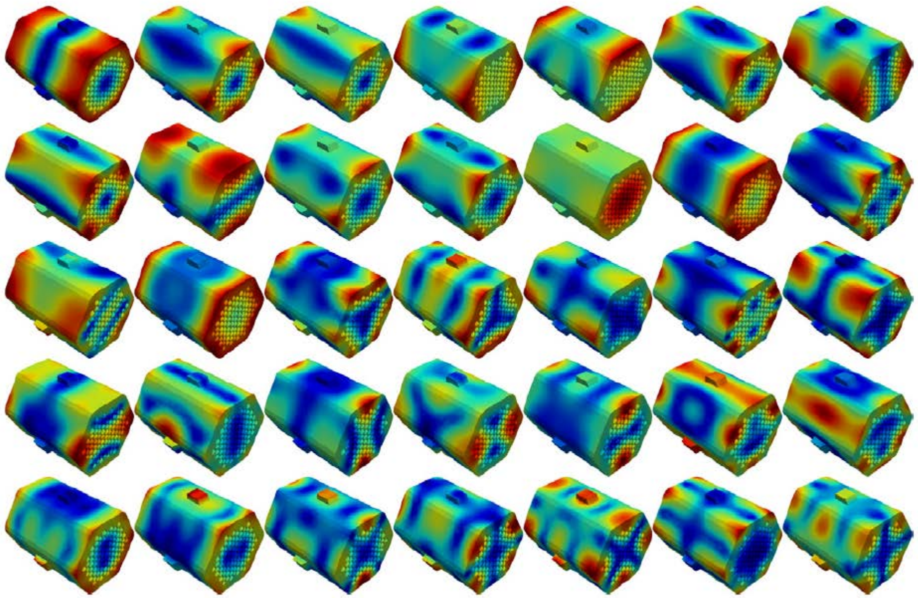
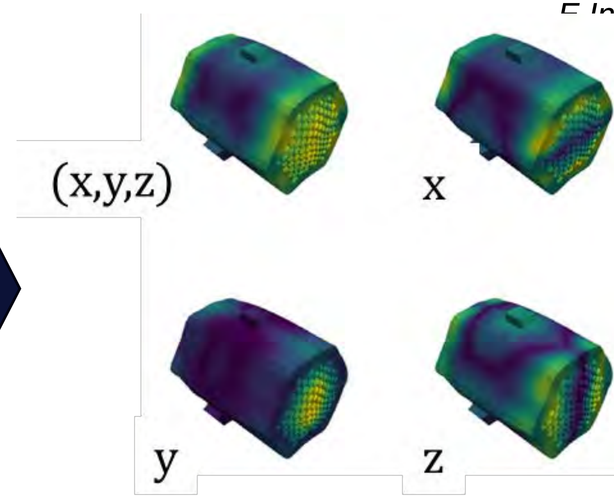
Predicting optimal sensor placement

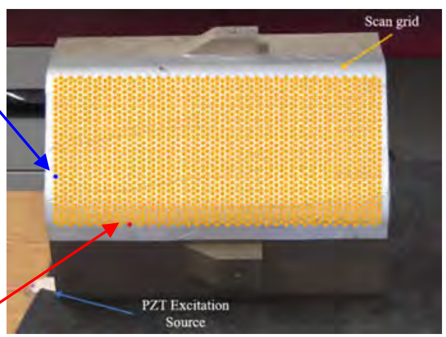


Beardslee, Shokouhi, **Ulrich** (2024). *NDT & E Intl.*



High-information density

Low-information density



- Prior to measurement: predict optimal sensor placement using principal component analysis (PCA) on mode shapes
- Regenerate analysis for any combination of physical components

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Takeaways of capstone project

- Mentorship provided for Masters-level data science capstone project at Texas A&M
- Neural network trained and tested on a subset of 2TB vibrational dataset from FY23 (1 input amplitude chosen out of 10)
- Prediction performance:
  - 81.2% accuracy for component of motion (**2.4x** better than random guess)
  - 51.2% accuracy for stress state (**2.6x** better than random guess)
- PCA provided best dimensionality reduction
- Suggested next steps: increase diversity of damage & stress states in training dataset
- Project has prompted interest from other data science students at A&M, plans for A&M to host data in open access repository

Model architecture
[# of units/neurons]

Flatten time series [50000]

Dense – ReLU activation [128]

Dropout – prevent overfitting (rate=0.5)

Dense [64]

Dropout

Output [3]

Next steps: experimental

- Collect new dataset on intact/damaged sample with an emphasis on activation of nonlinear elastic behavior for damage detection
  - Unify data acquisition settings to improve ML processing
  - Utilize infrared vibrometry for improved sensitivity to mode shapes during excitation
- Refine data acquisition processes for implementation in reactor test bed

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Questions for potential implementation at MARVEL

- What are the expected vibration sources?
  - Frequency bandwidth, amplitude, propagation distance
- Are there opportunities to make exploratory measurements with a laser vibrometer or will any measurements require embedded transducers or fiber optic?
  - Which high-concern components/systems/materials can be monitored in-situ?
  - Core block, heat pipe, interfaces, other non-rad components?

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FY24 milestone status

Completed: Develop plan for integration with ORNL embedded sensing advancements (M4 carryover from FY23)

In-progress and on track:

1. Evaluate methods of machine learning, FE modeling, and analysis using prior demonstration data for defect localization and other metrics (M4, due Mar 2024)
2. Integrate selected processing methods, analytical techniques, and new acoustic data for defect localization and other metrics (M3, due Sep 2024)

Recent MRP-supported papers & presentations

Beardslee, L., Shokouhi, P, and **Ulrich, T.J.** (2023). Optimal measurement point selection for resonant ultrasound spectroscopy of complex-shaped specimens using principal component analysis. *Nondestructive Testing & Evaluation International.*

Conference Presentations

Geimer, P.R., **Ulrich, T.J.**, Moore, J.R. (2023, June 5–9). *Modeling quantification of nonlinear resonant ultrasound spectroscopy* [Conference presentation]. 25th International Conference on Nonlinear Elasticity in Materials, Ghent, Belgium.

(invited) **Geimer, P.R., Beardslee, L., Ulrich, T.J.** (2023, December 4-8). *Nonlinear resonant ultrasound spectroscopy using white-noise excitation.* [Conference presentation]. Acoustics 2023, Sydney, Australia.

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