Evaluation of Ultrasonic Battery Inspection Techniques

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SPIE Smart Structures + NDE
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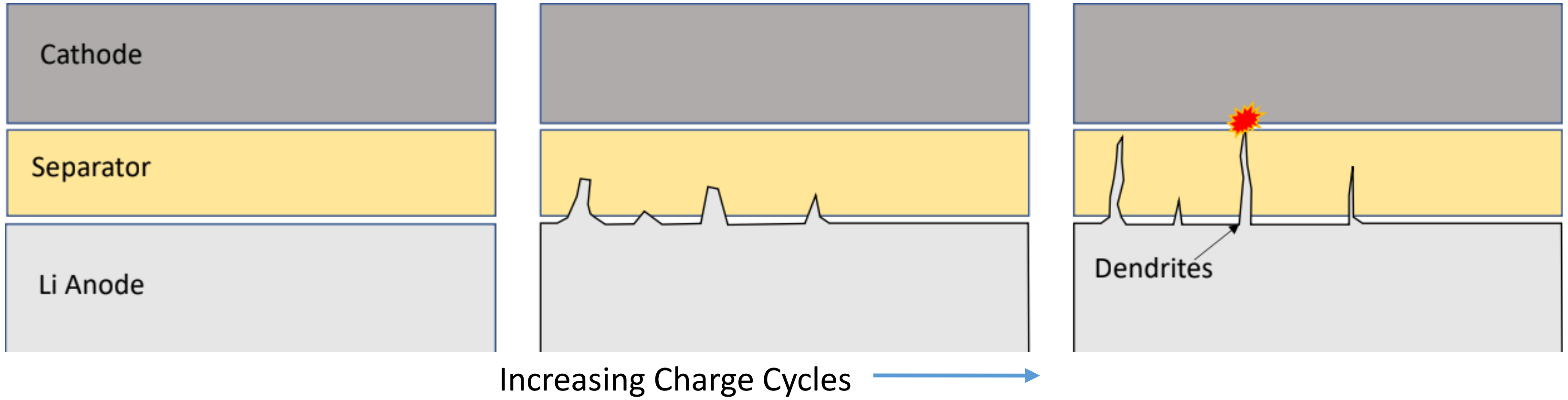
Motivation

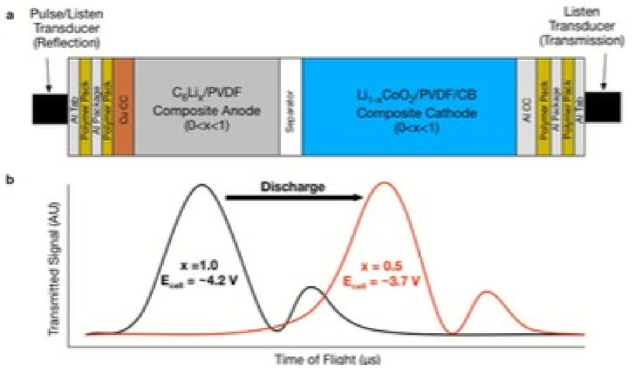
- Higher energy density batteries are needed to meet aerospace demands
- Many high energy density configurations use lithium (Li) metal anodes
- Non-uniform Li anode plating can lead to dendrite growth, short circuit, and thermal runaway
- <u>Research Goal</u>: Identify local changes in structure that could lead to thermal runaway through nondestructive evaluation (NDE)

Illustration of lithium dendrite growth leading to internal short circuit

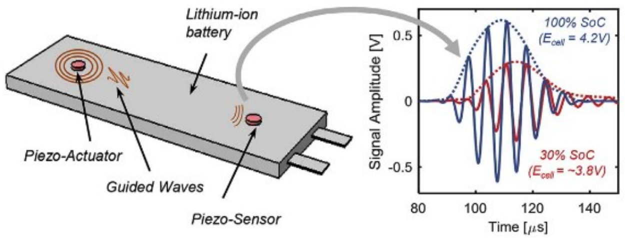


Prior Work on Ultrasonic Testing (UT) of Batteries

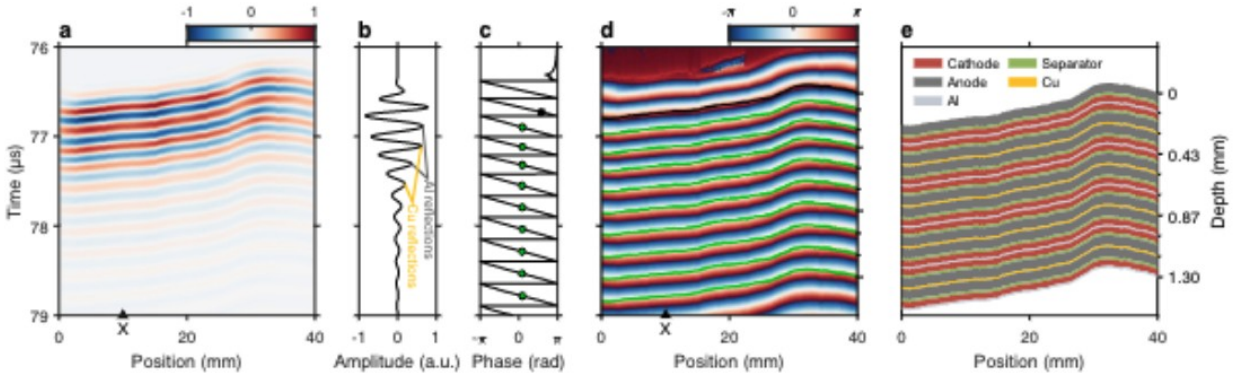
- Hsieh[1] used elastic property changes due to ion transport to assess state of charge (SOC) and state of health (SOH)
- Ladpli[2] applied guided wave UT using external piezoelectric sensors to detect SOC and SOH
- Huang[3] applied time domain and resonance analysis to track changes in structure as a function of SOC and SOH



[1]A. G. Hsieh, et al., *Energy and Environmental Science,* 2015



[2]P. Ladpli et al., *Journal of Power Sources,* 2018



[3]M. Huang et al., *Journal of Energy Storage,* 2022

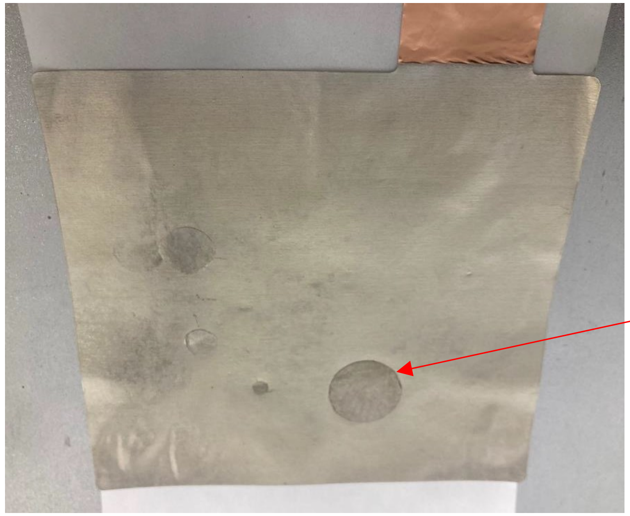
Battery NDE is an emerging field mostly focused on SOC and SOH

Specimens for Evaluating Flaw Sensitivity

- A pouch cell Li-metal battery was seeded with anode defects to test sensitivity of ultrasonic approaches
- Pouch cell structure:
  - Single battery cell (one anode/cathode pair)
  - $LiCoO_2$ cathode material
  - Porous polymer separator
  - Li metal anode with 80 um Li chips pressed onto the surface
  - Liquid electrolyte

Pouch cell layup:

Pouch
Celgard 2325
Li Defect
Li
Cu
Li
Celgard 2325
$LiCoO_2$
Al
$LiCoO_2$
Celgard 2325
Pouch



Li metal anode with 80um thick lithium chip defects

Li chip Defects

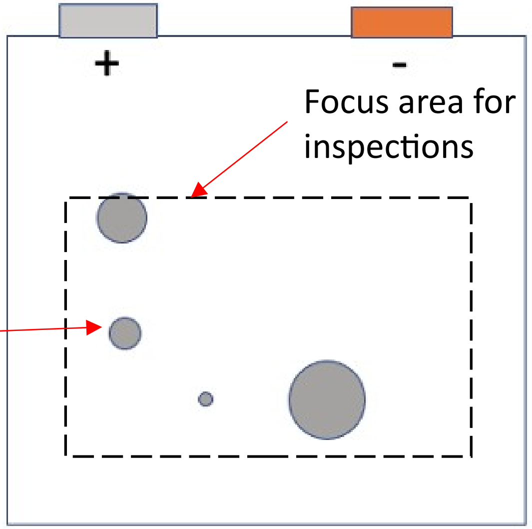


Illustration of pouch cell defect locations

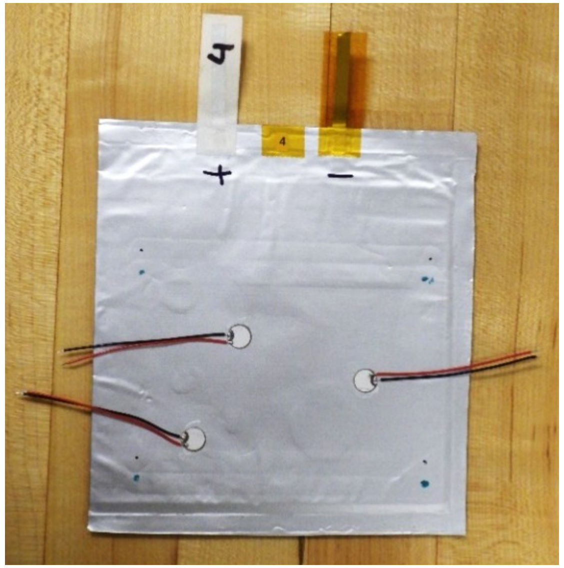
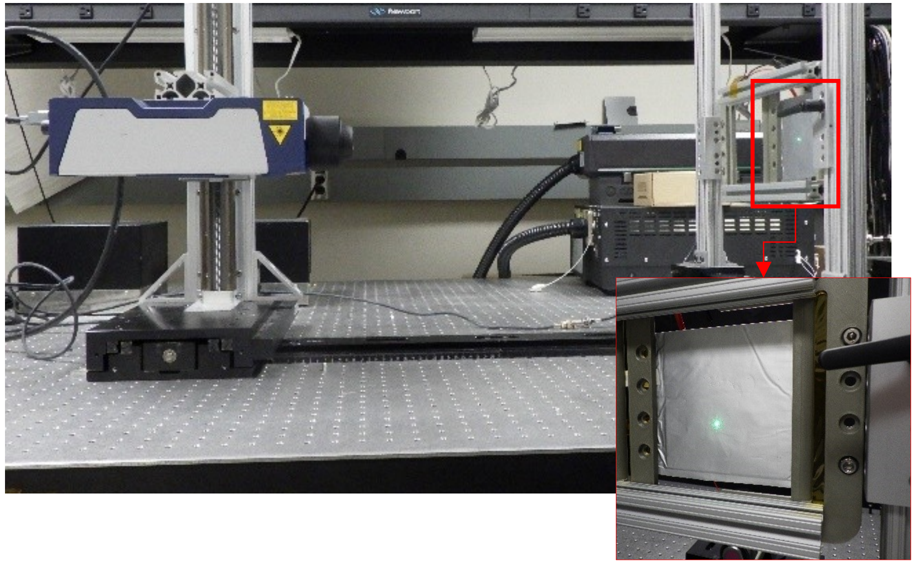


Image of Battery

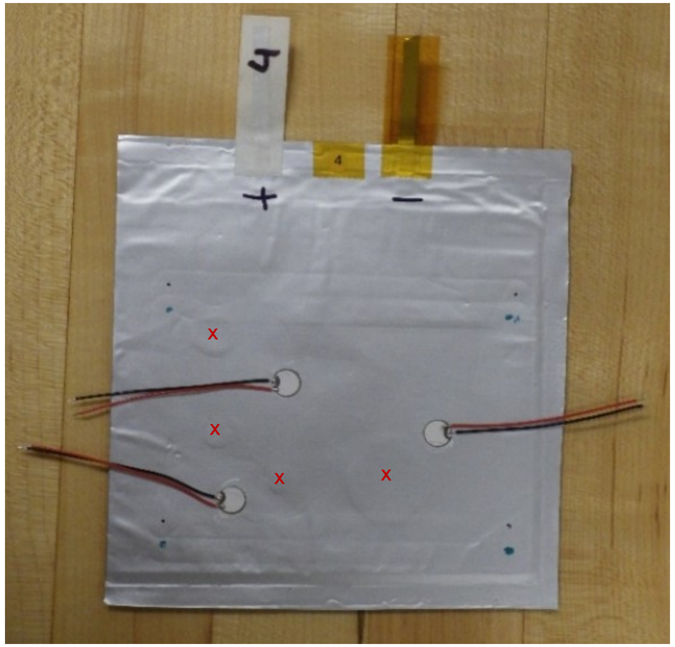
Overview of Guided Wave Approaches

- Guided wave ultrasound involves propagation of waves along boundaries
- Two guided wave ultrasound methods:
  - Pitch-catch testing via piezoelectric wafer active sensor (PWAS)
  - Laser Doppler vibrometry (LDV) – line scans

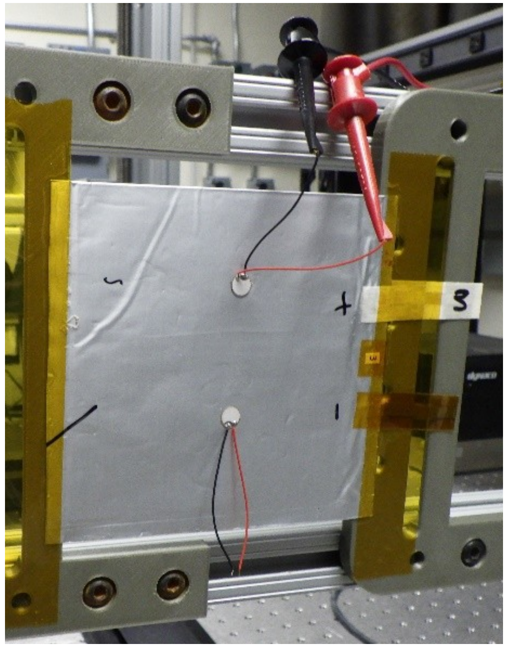
LDV Experimental Setup

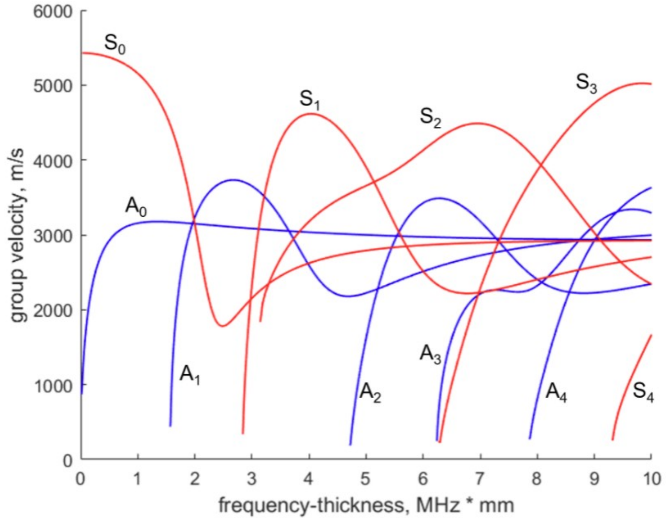


Defective Cell



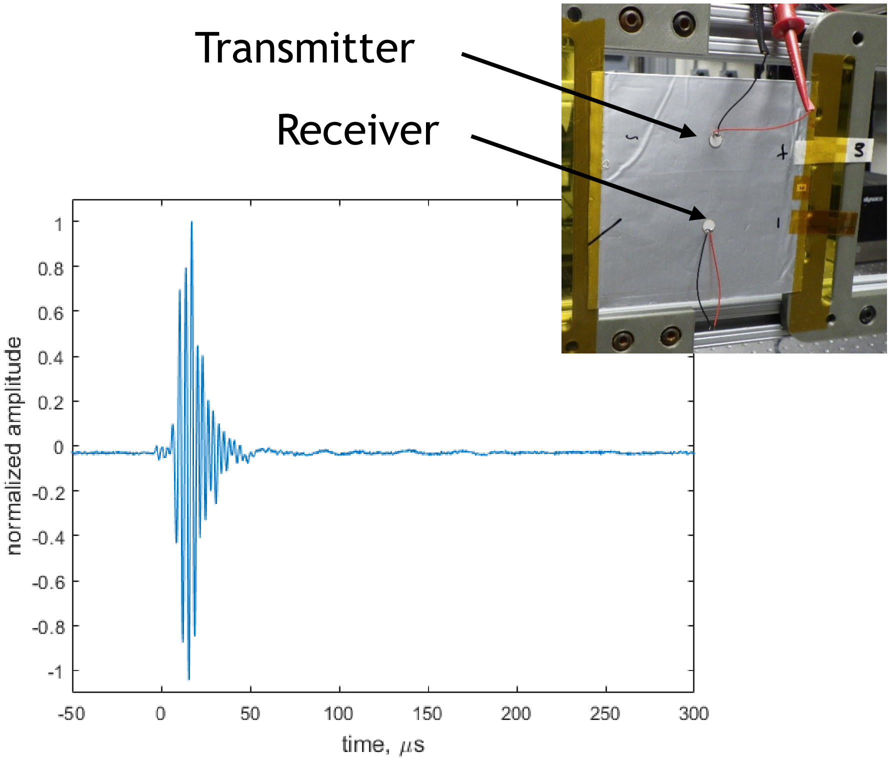
Baseline Cell



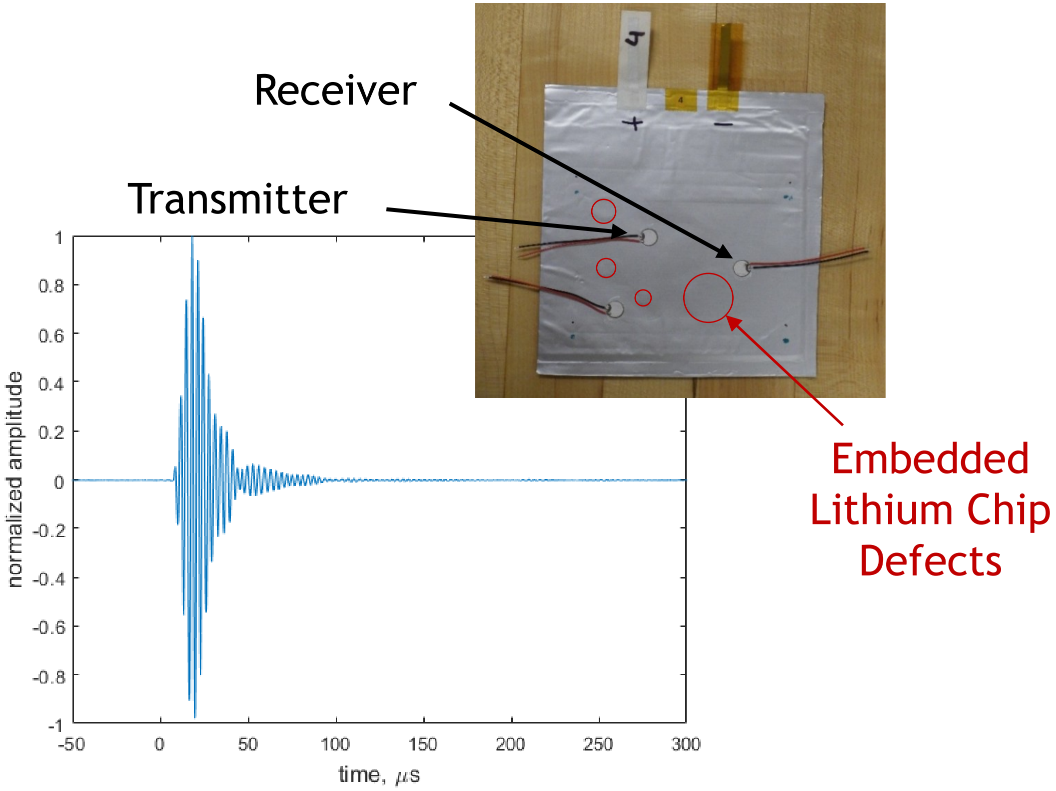


Example group velocity dispersion curve

Pitch-Catch Guided Waves



Pristine pouch cell



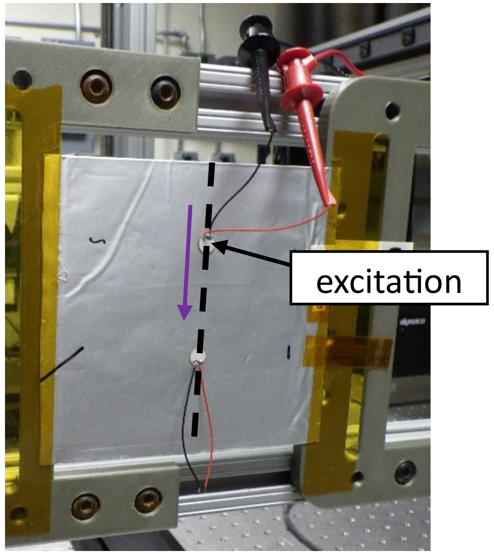
Defective pouch cell

- PWAS bonded to battery pouch using cyanoacrylate adhesive
- Excited using a 20 V_{pp} 300 kHz, 3-count sine wave
- Clear wave mode measured at receiver with high signal-to-noise ratio (SNR)
  - ‘Ringing’ observed due to large Li chip next to receiver in defective pouch cell

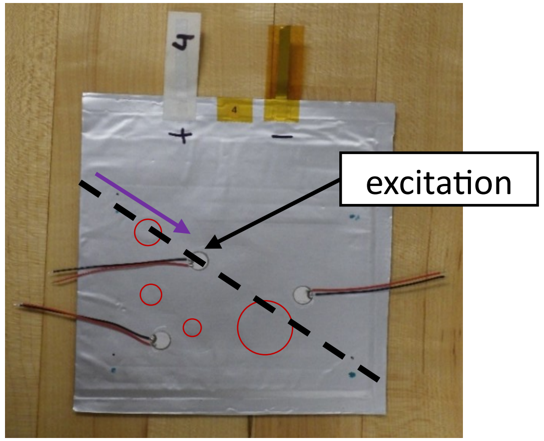
Laser Doppler Vibrometry - Line Scans

- PWAS excited by a 5 V_{pp}, 5-count Hanning windowed sine wave
- LDV line scans
  - Detection of out-of-plane velocity
  - 100 µm steps, 128 averages per point
- Two wave modes present in pristine pouch
  - Identified by two distinct slopes/velocities
- Three wave modes present in defective pouch
  - Rippling present for propagation over aberrations, may be due to factors such as defects and pouch wrinkling

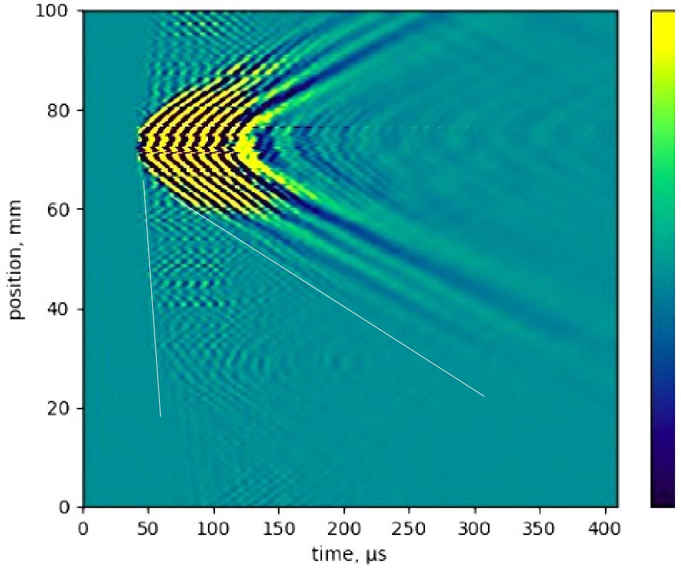
Pristine

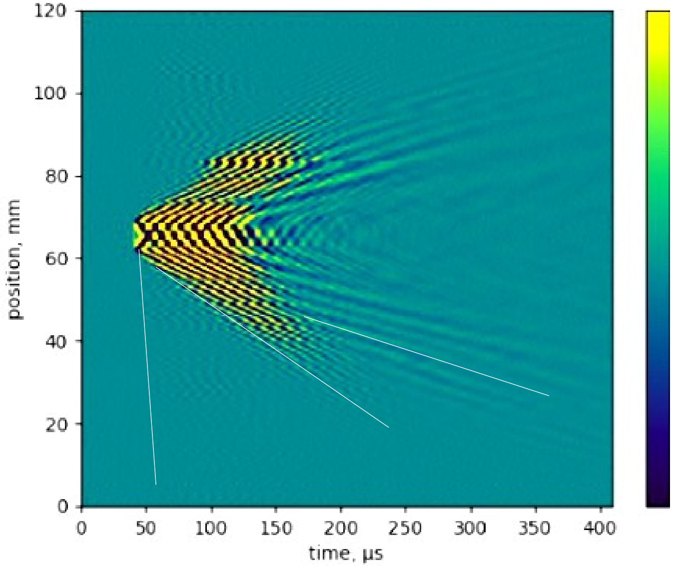


Defective



Line scan across black dotted lines, in direction of purple arrow

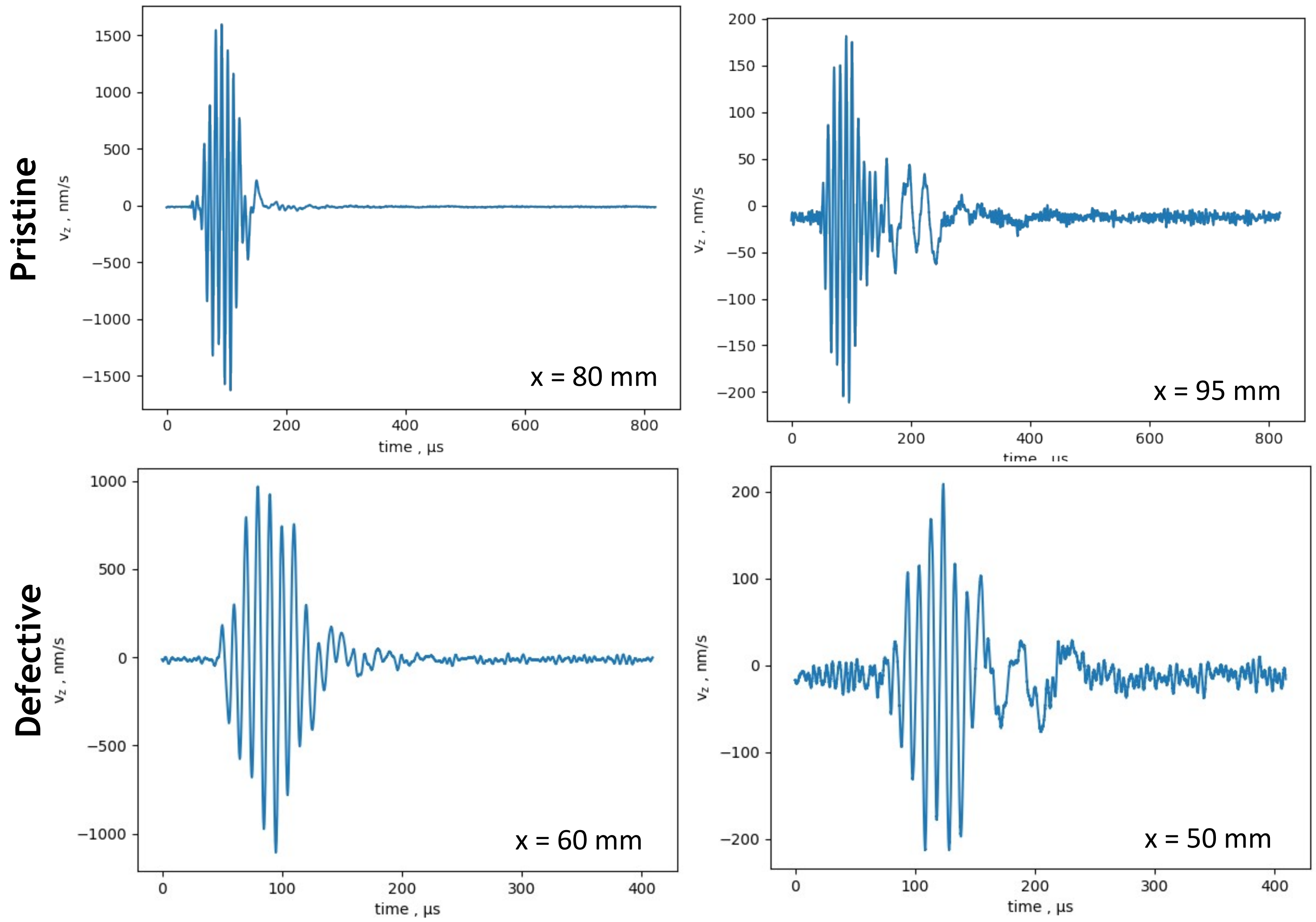




LDV B-Scans

Laser Doppler Vibrometry – Waveforms

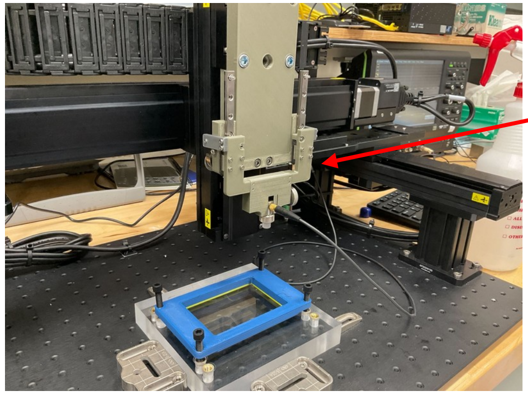
- Waveforms via LDV at individual locations
  - x=0 location beginning of scan line
- Wave mode separation observed (probable fundamental symmetric / antisymmetric)
- Significant attenuation over small propagation distances – electrolyte viscous effects
  - Tradeoff with PWAS pitch-catch – LDV obtaining spatial data at lower SNR



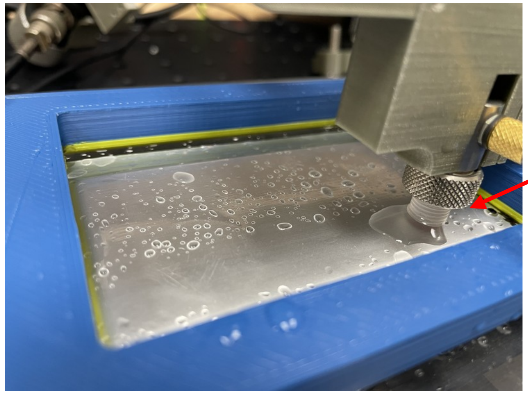
Local Ultrasonic Resonance Spectroscopy (LURS)

- Assesses through-thickness resonances, which are affected by layup and constituent properties
- Demonstrated by Rus and Grosse[4] on plate specimens and applied to battery inspection by Nelson[5]

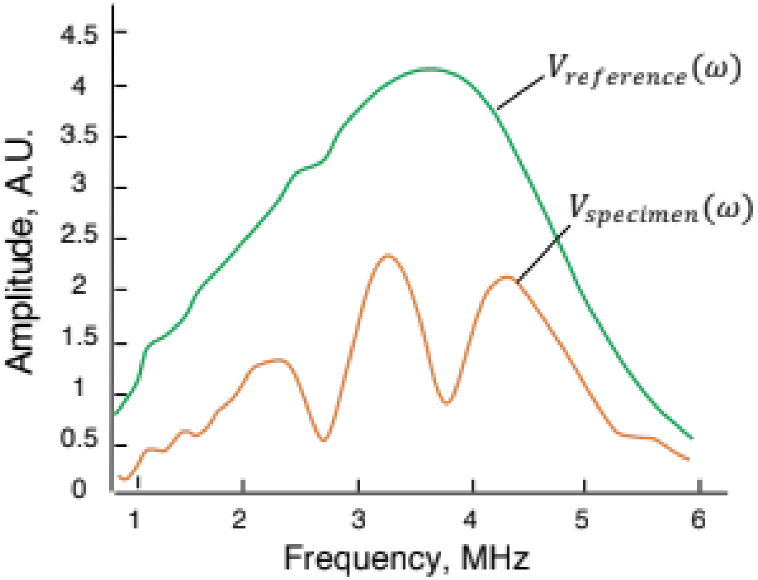
Scanning gantry and custom fixturing used for collecting contact data

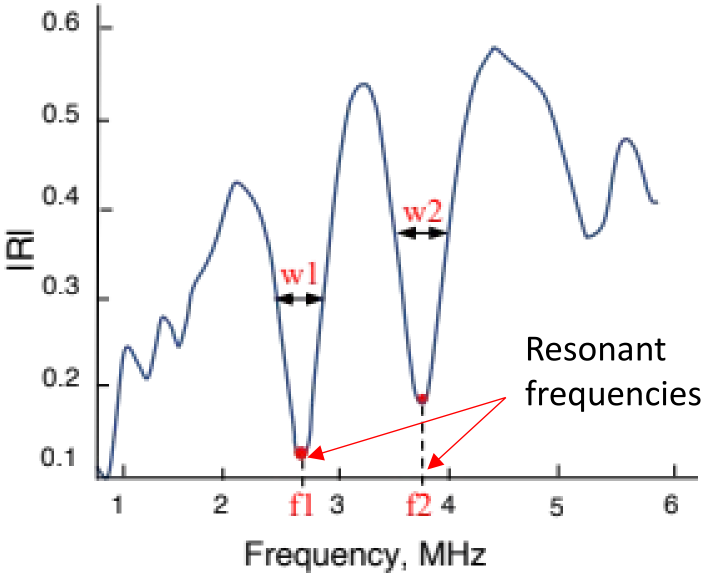


Constant force measurement probe



Transducer with delay line





Resonant frequencies

Frequency-dependent reflection coefficient

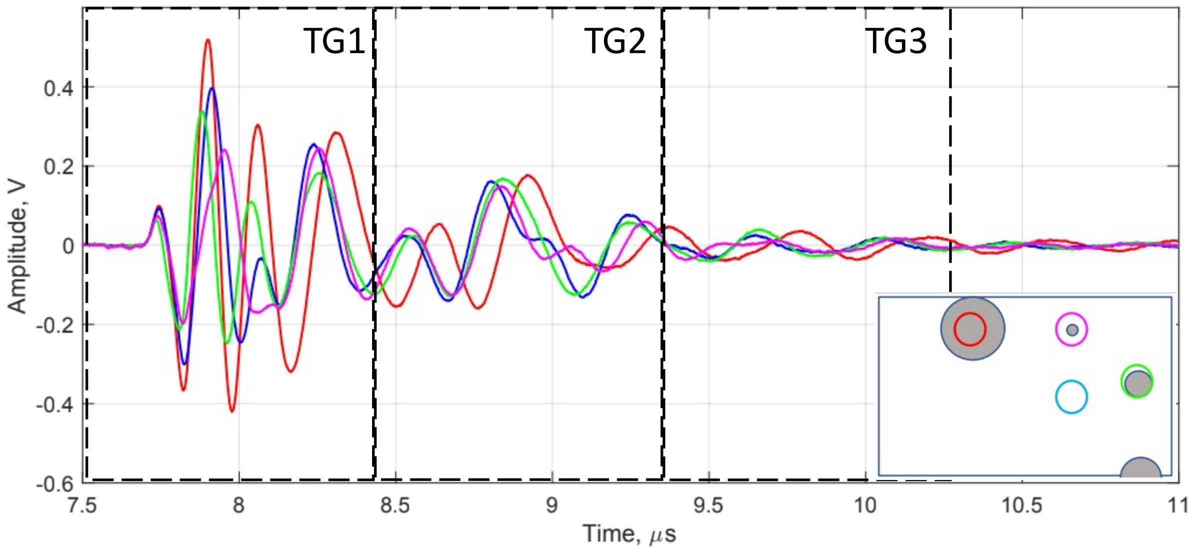
$$|R(\omega)| \quad \frac{V_{specimen}(\omega)}{V_{reference}(\omega)}$$

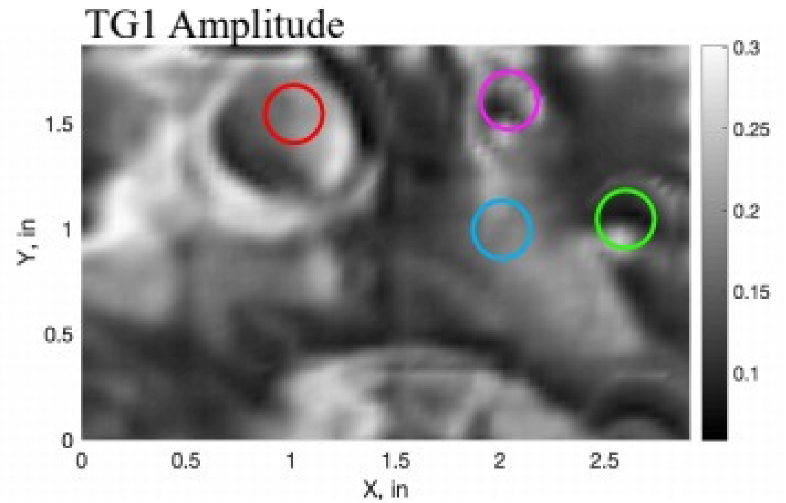
[4] J. Rus and C. Grosse, “Local Ultrasonic Resonance Spectroscopy: A Demonstration on Plate Inspection”, *J. NDE*, 2020.

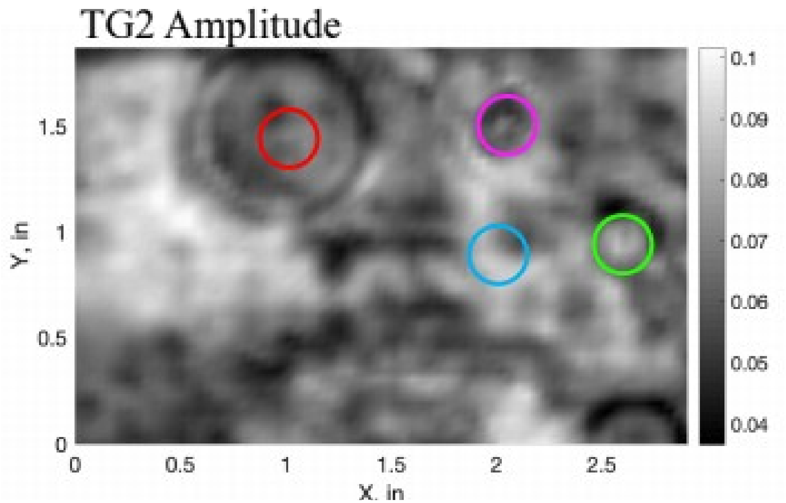
[5] W. Nelson, "Local Ultrasonic Resonance Spectroscopy of Lithium Metal Batteries for Aerospace Applications." *Master’s Thesis, University of Virginia* (2021).

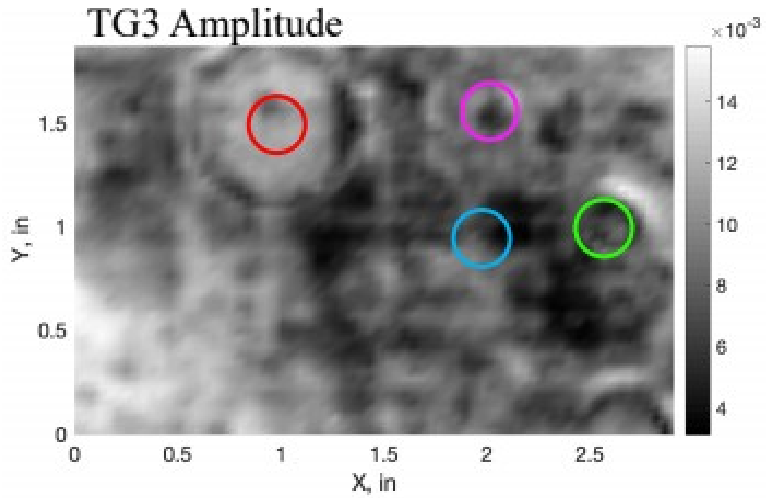
Time-domain Amplitude

- Time domain analysis data shows signatures from embedded flaws
- Surface and edge effects present early in the received signal





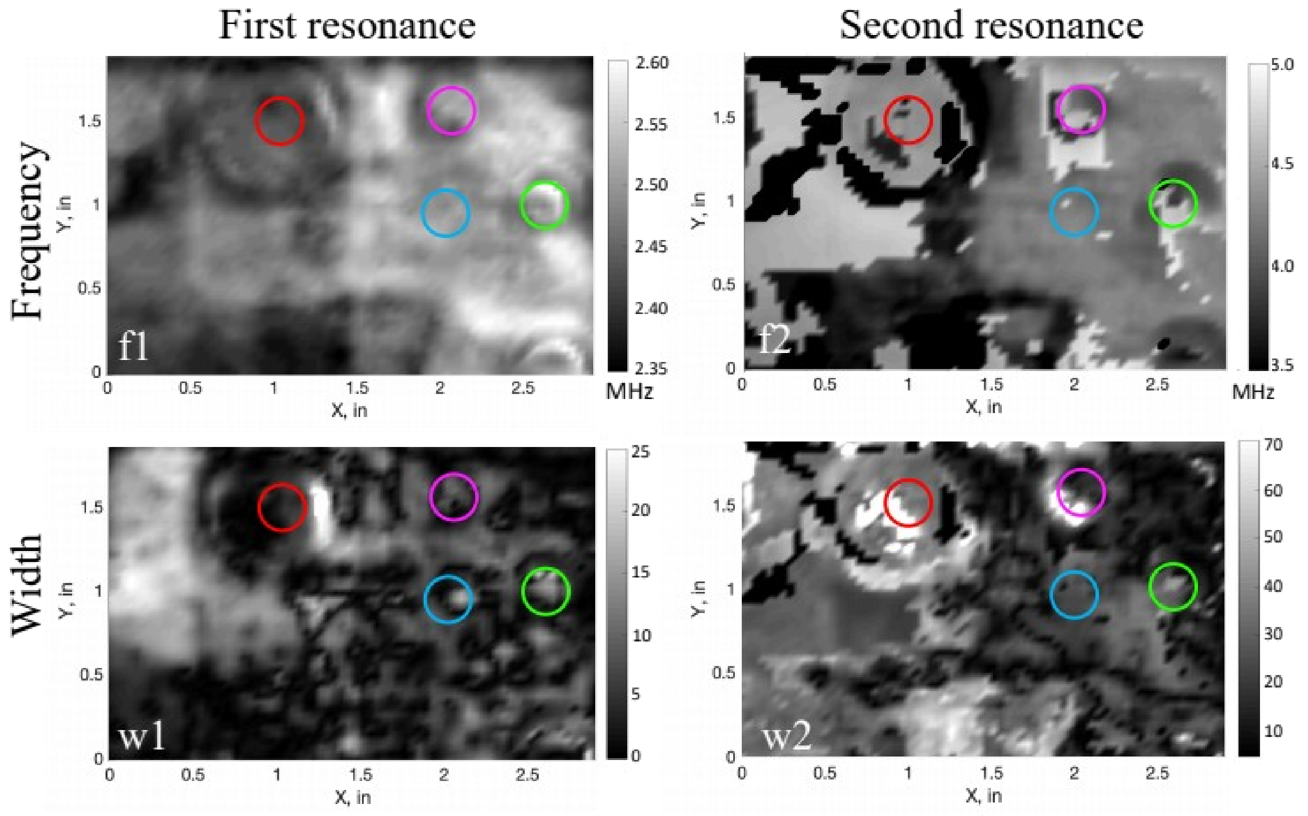


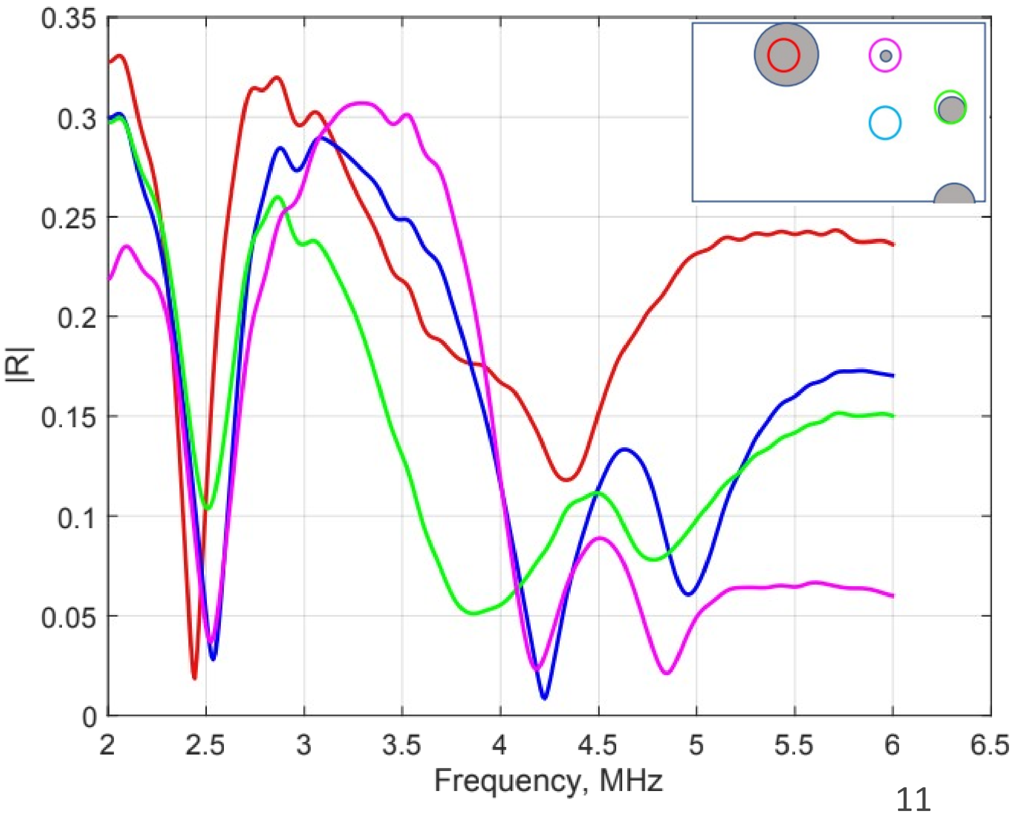


Resonance Frequency Analysis

- Flaw cause shift in first and second resonance frequency with most dominant effects in second resonance
  - Most dominant shift in the second resonance frequency (f2)

- Some areas without known defects show signs of differences in structure as well

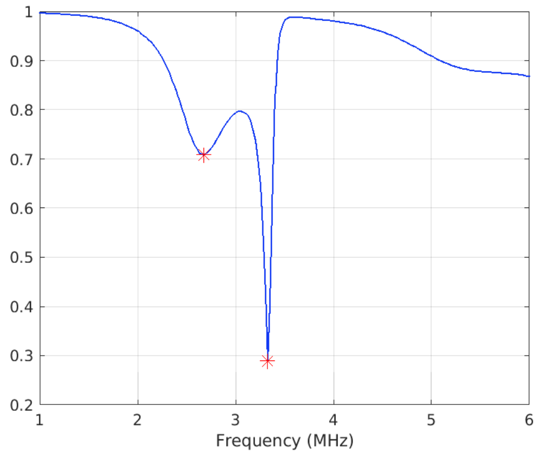




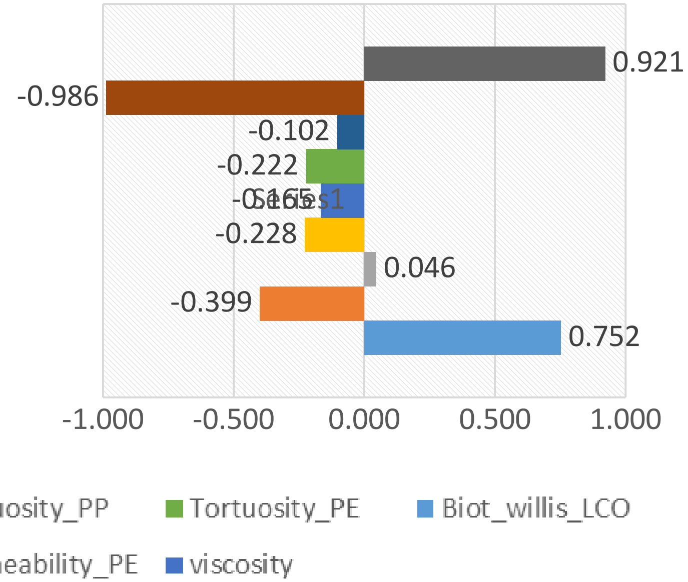
Emerging Techniques – Model Parametric Exploration

- Linking forward model with Dakota software, from Sandia National Laboratory https://dakota.sandia.gov/
  - Simulated reflection spectrum in COMSOL using two-dimensional elastic-poroelastic media, technique via Nelson[5]
- Sensitivity analysis, surrogate modeling, and inversion techniques for applications like material property, geometry, and flaw inverse analysis

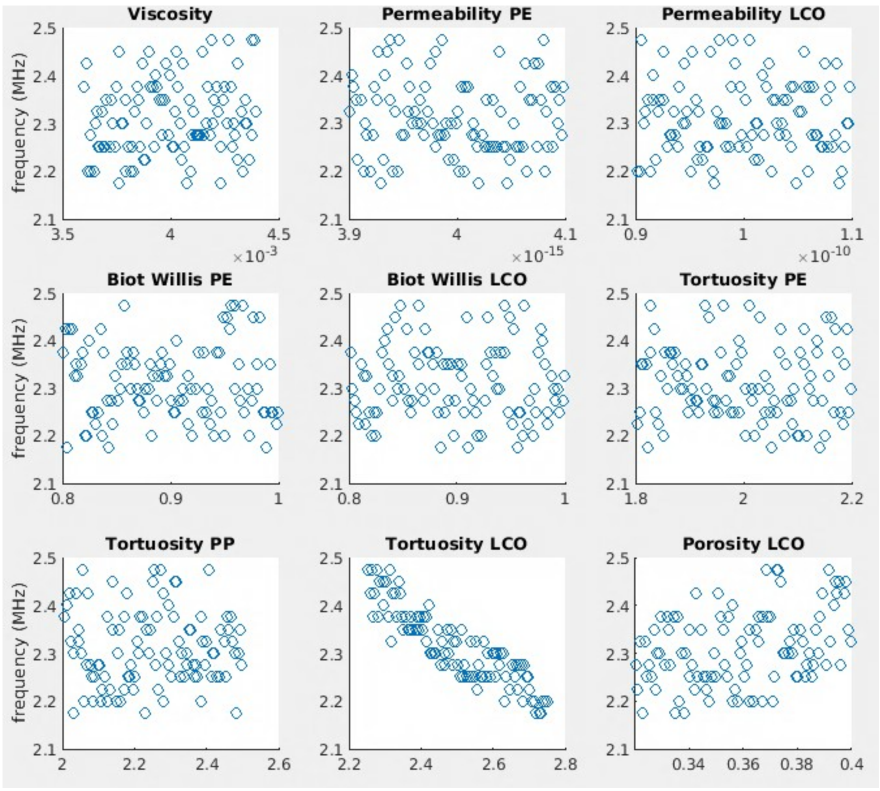
Resonance spectrum –
2D elastic-poroelastic simulation in COMSOL



Fundamental resonance, partial rank correlation



Sensitivity of resonance to material parameters



[5]Nelson, William Charles. "Local Ultrasonic Resonance Spectroscopy of Lithium Metal Batteries for Aerospace Applications." *Master's Thesis, University of Virginia* (2021).

Discussion

- This study demonstrates two candidates for identifying local changes in structure in lithium-metal batteries
- Guided wave ultrasound is viable for in situ inspection, with pitch catch showing particularly good signal/noise and sensitivity to lithium defects
- LURS provides much more information on the local structure than available from conventional pulse-echo inspection
  - Inverse modeling framework established for calibration and sensitivity analysis
  - Still needs to be implemented for inspection data
- Currently working with battery subject matter experts to develop realistic damage so that these techniques can be evaluated for prognostic capability

Acknowledgements

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- Specimens manufactured by Cornerstone Research Group