



Property Estimation in Thin Battery Components Using Guided Wave Measurement: Experimental Dispersion Curve Extraction and Finite Element Modeling

Quantitative Nondestructive Evaluation

July 25-27, 2022



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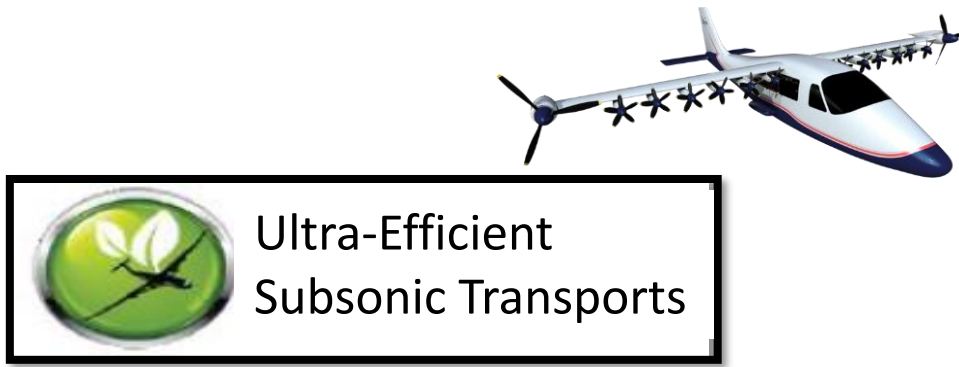
Next Generation Electric Propulsion

Emerging electric aircraft concepts need better performing, safer energy storage



A **safe**, high energy battery will disrupt the electric aircraft industry

Alignment with NASA Strategic Thrusts



2025

2030

2035



Safe, Efficient Growth
in Global Operations

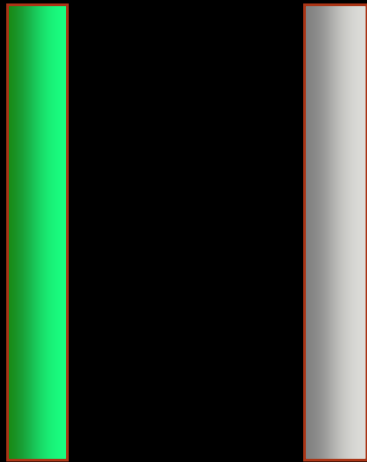


Safe, Quiet and
Affordable Vertical Lift Air
Vehicles



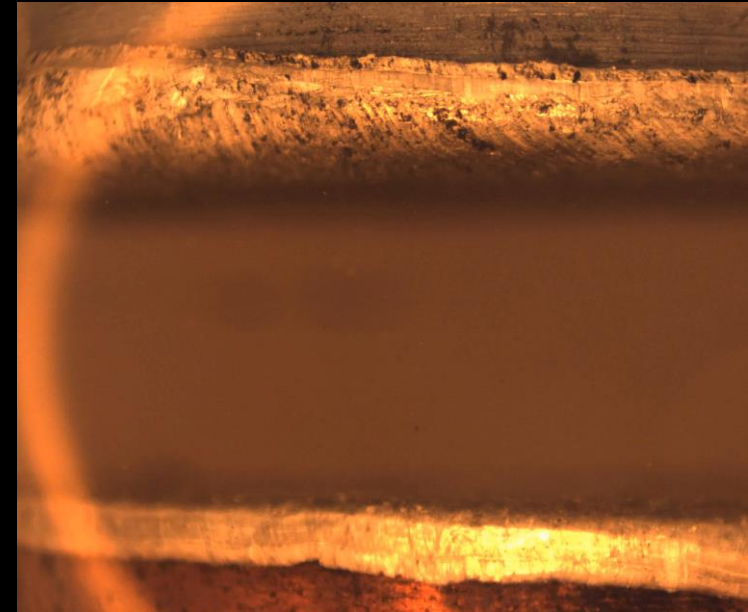
In-Time System-Wide
Safety Assurance

Dendrite Growth and Thermal Runaway



Lithium Ion ●

Dendrite growth during
charge/discharge



Laboratory growth of 'mossy' dendrites
in Li/Li battery

Dendrite Growth and Thermal Runaway



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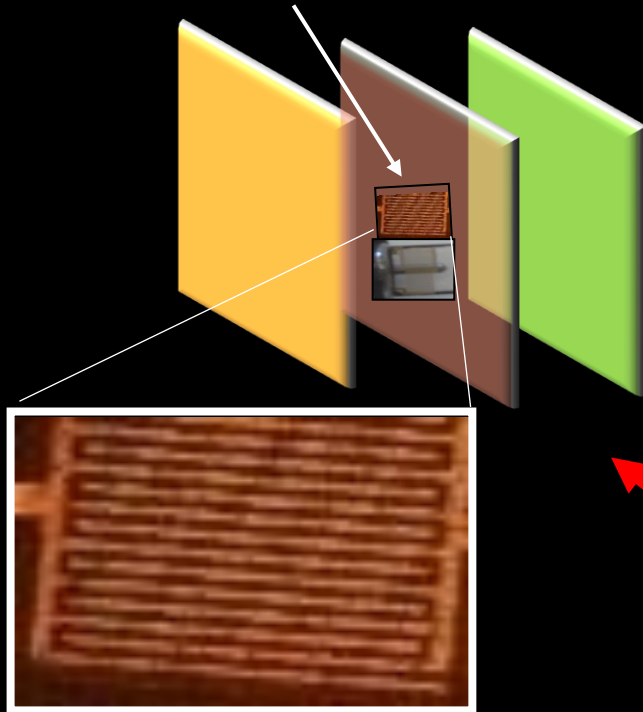
Lithium-ion battery cells externally heated to induce thermal runaway.



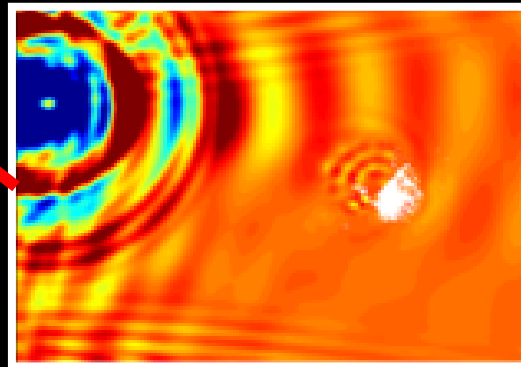
SPARRCI

Sensor-based **P**rognostics to **A**void **R**unaway **R**eactions and **C**atastrophic **I**gnition

Cell-embedded sensors

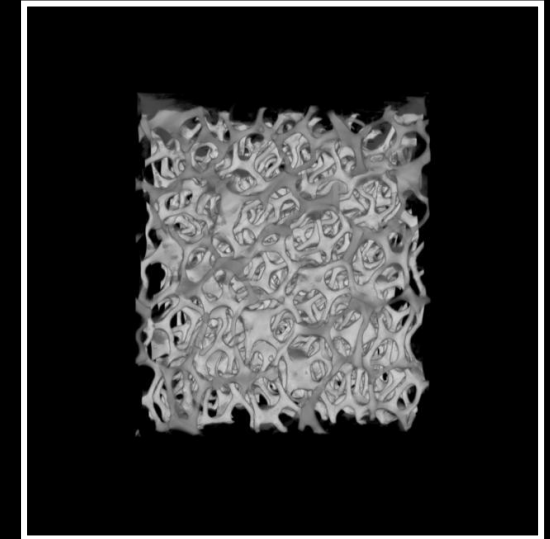


Physics-based
NDE Modeling



Ultrasonic waves modeled in
composite structure

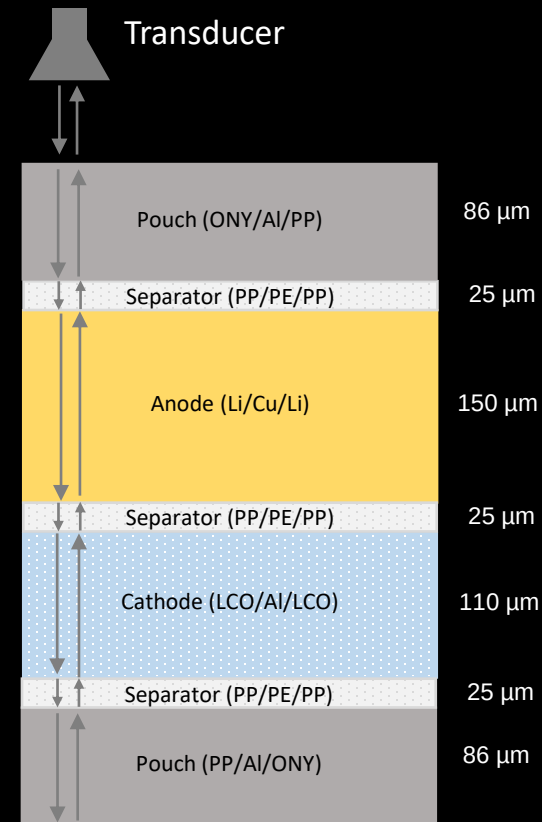
Nondestructive Evaluation



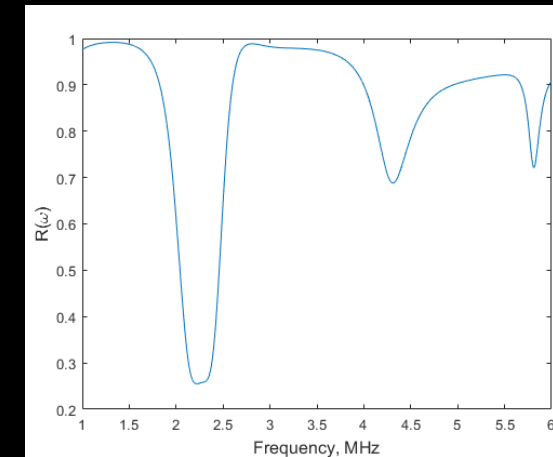
X-ray CT of metallic foam

Physics-based NDE Modeling

- Emerging capabilities in ultrasonic nondestructive evaluation (NDE) and structural health monitoring (SHM)
 - State of charge (SOC) and state of health (SOH) monitoring (Gold et al. 2017, Lapdli et al. 2017)
 - A few studies & emerging capabilities for defect detection (Bommier et al. 2020, Nelson 2021)
- Components with heterogeneous, complex media, and non-stationary properties
 - NDE modeling to help manage complexity of inspection/monitoring
- Material model: combination of elastic and fluid-filled porous (poroelastic) media models
 - Significant number of material parameters that need to be obtained or inferred



Concept sketch of single-cell through-thickness resonant measurement



Example of a simulated Li-metal pouch cell reflection spectrum

Poroeelastic Material Properties

Solid components
(current collectors, pouch material, Li
electrode)

ρ Density
 E Young's Modulus
 ν Poisson Ratio

Porous components
(Separator, Anode)

β Porosity
 ρ_s Density, solid material
 k_s Bulk modulus, solid material
 d Pore diameter
 k Darcy's permeability coeff.
 k_b Bulk modulus, drained matrix
 N_n Shear modulus, drained matrix
 α Tortuosity

Fluid Components
(electrolyte)

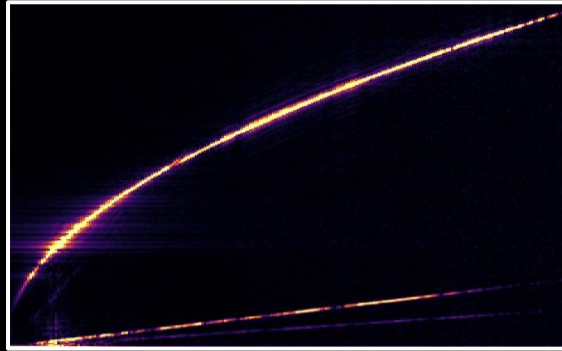
ρ_f Density
 k_f Bulk Modulus
 μ Viscosity

- “Need to have” properties: affect key spatial propagation characteristics (wave speeds, reflections)
- “Nice to have” properties: affect frequency-dependent behavior and frequency limits
- “Expect to Calculate / Infer” properties: affect spatial propagation, but are not expected to be in the literature
- Expecting to be able to calculate / infer some missing parameters from wave propagation experiments

Material Property Estimation Approach

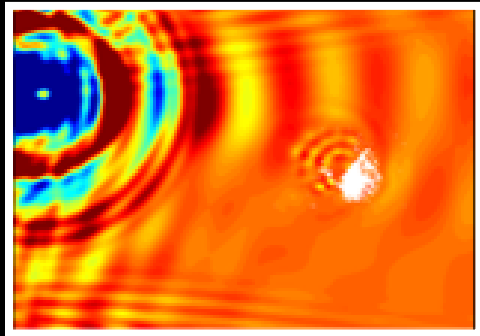


Experimental observation of
guided wave fields

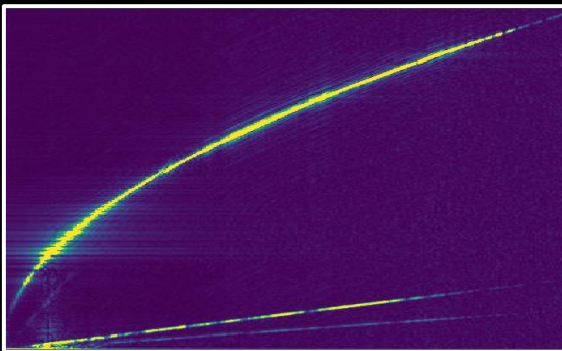


Extract dispersion curves from
data

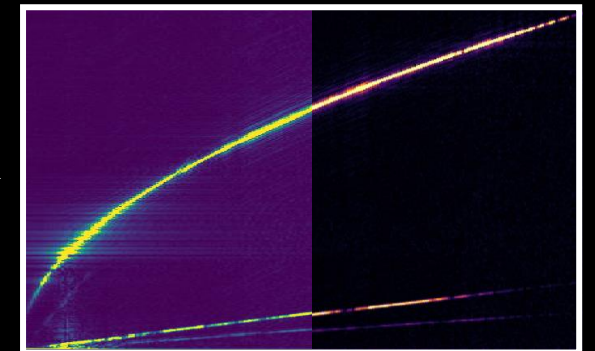
Calculate the missing
material property using
guided wave relations
(in this case, plate wave
approximations)



Generate simulation of wave
field using calculated properties



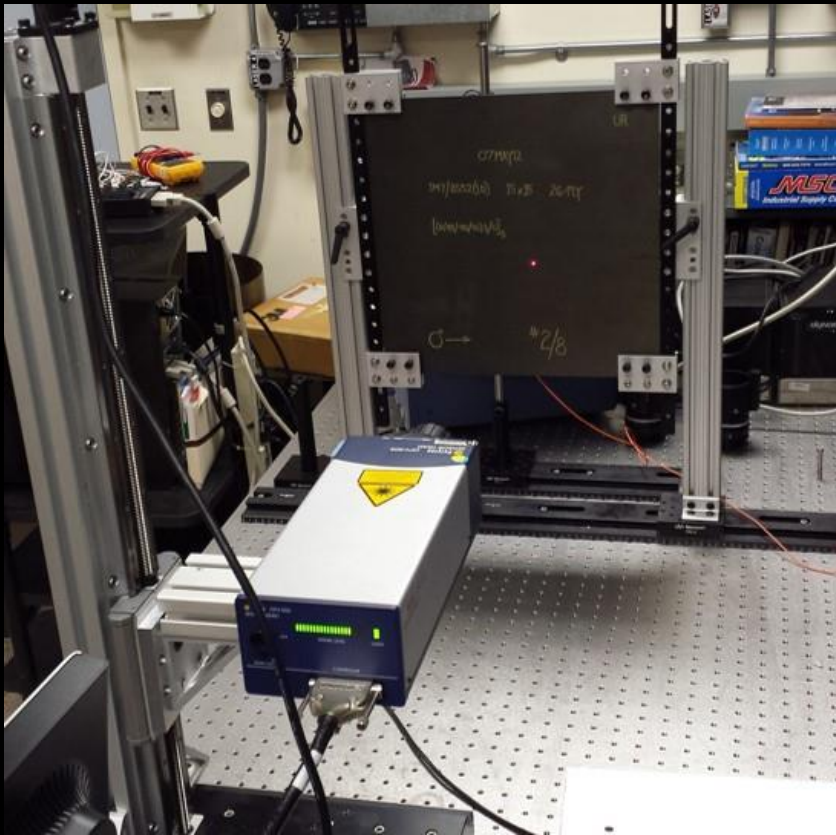
Extract dispersion curves from
data



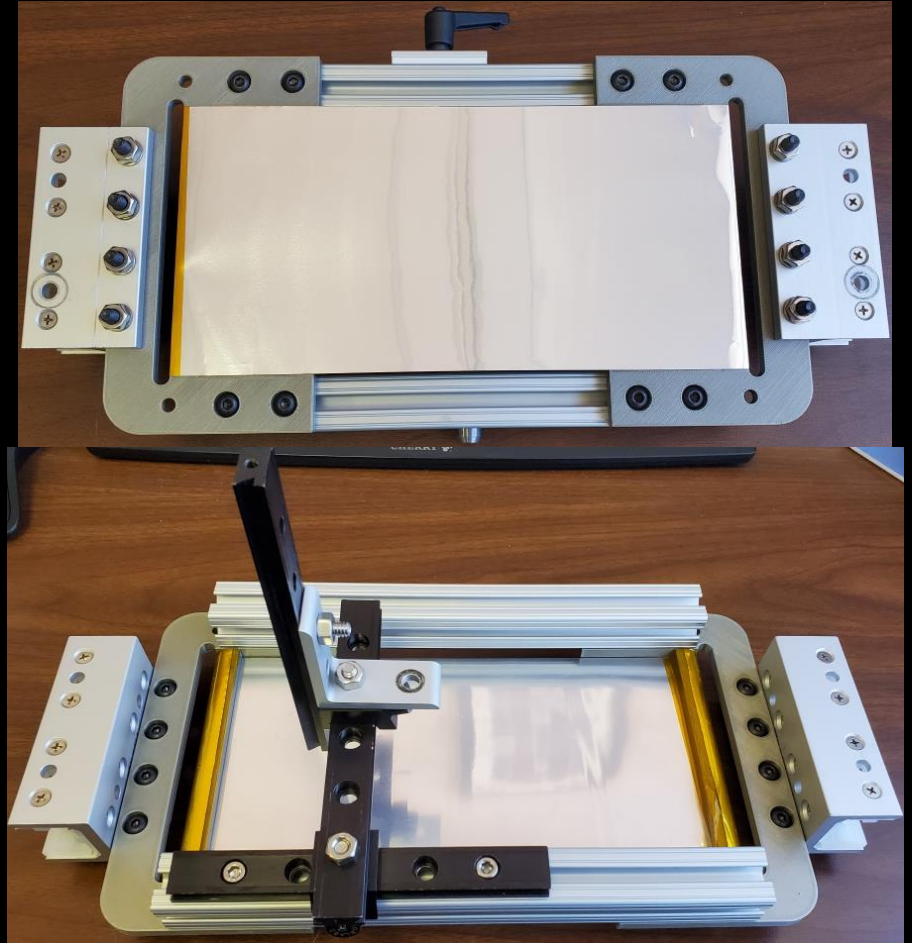
Compare experiment with
simulation

Experimental Setup

Laser Doppler Vibrometer (LDV)



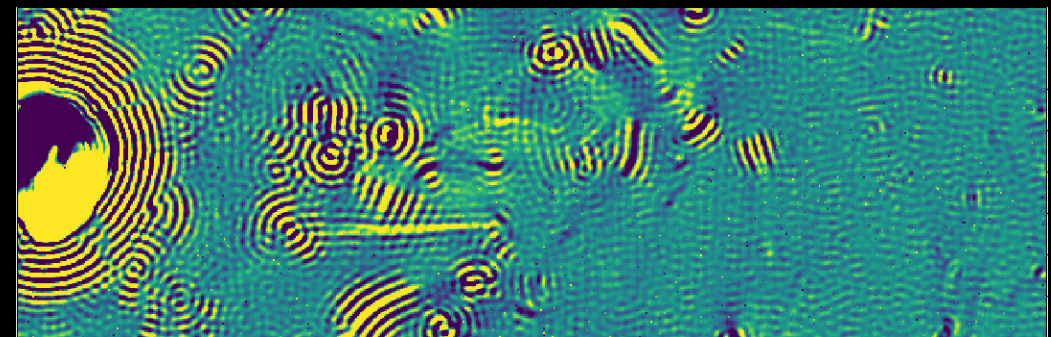
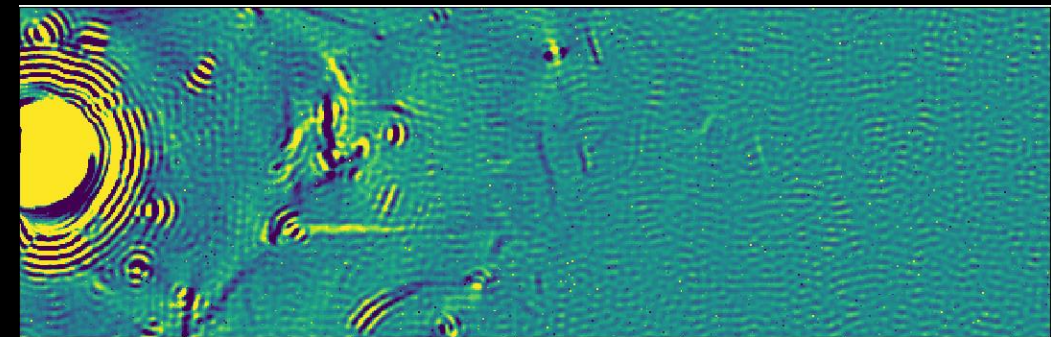
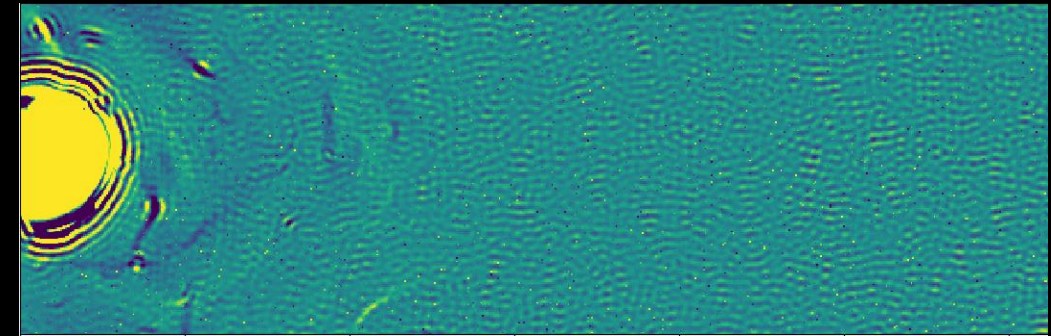
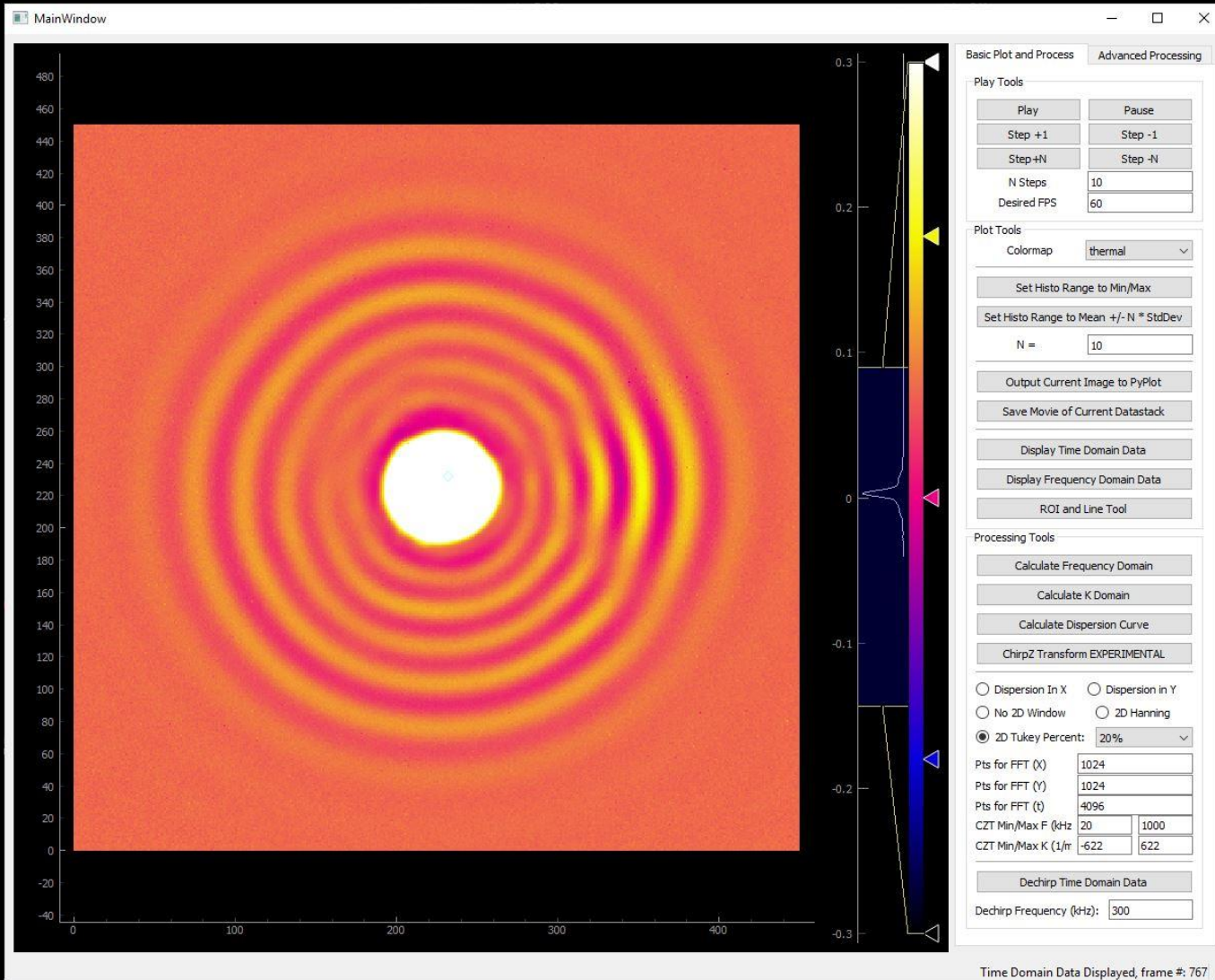
Thin Material Mounting Rig



LDV Results on Thin Cu Foil

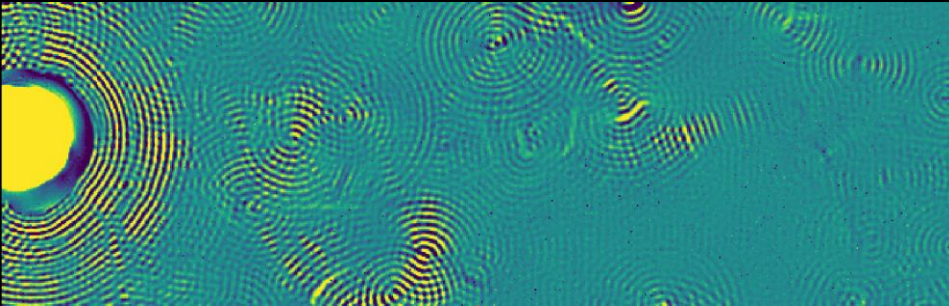
Data Processing GUI

Wave field in copper 110 foil

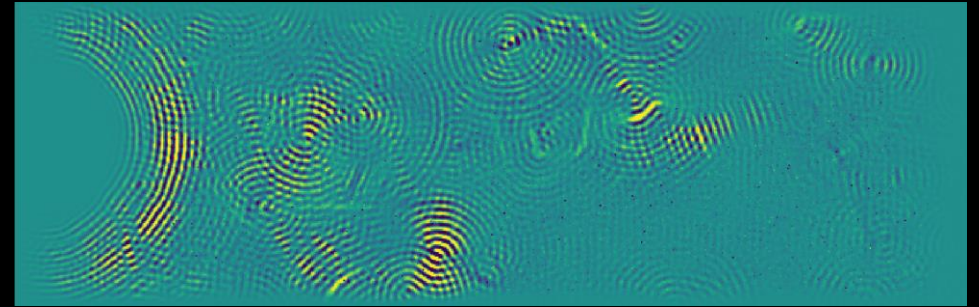


Data Processing

Raw Data



Apply window filter to data



Tukey windowing around edges



+

Hanning-based window around transducer

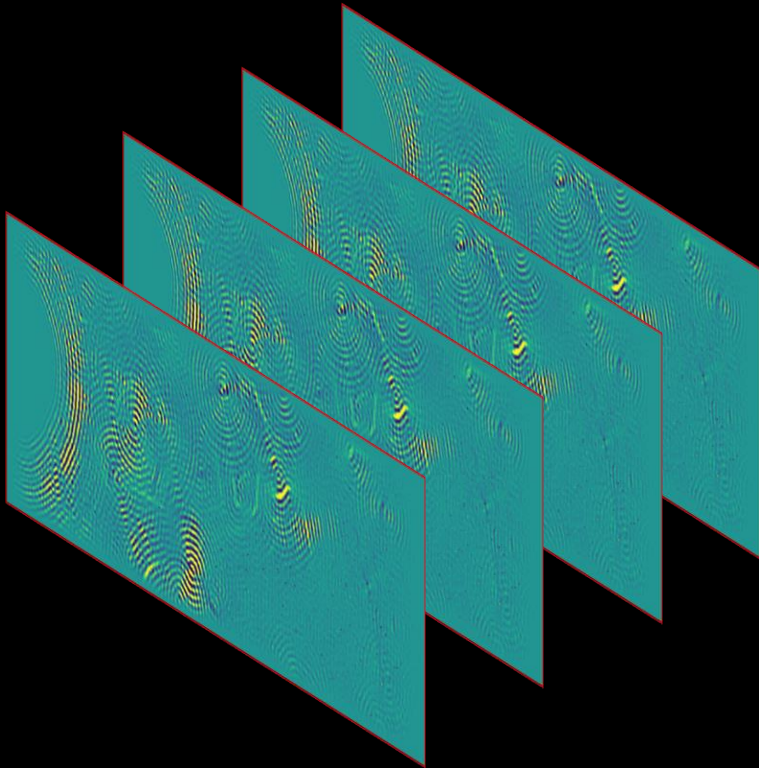


Combine both spatial windows



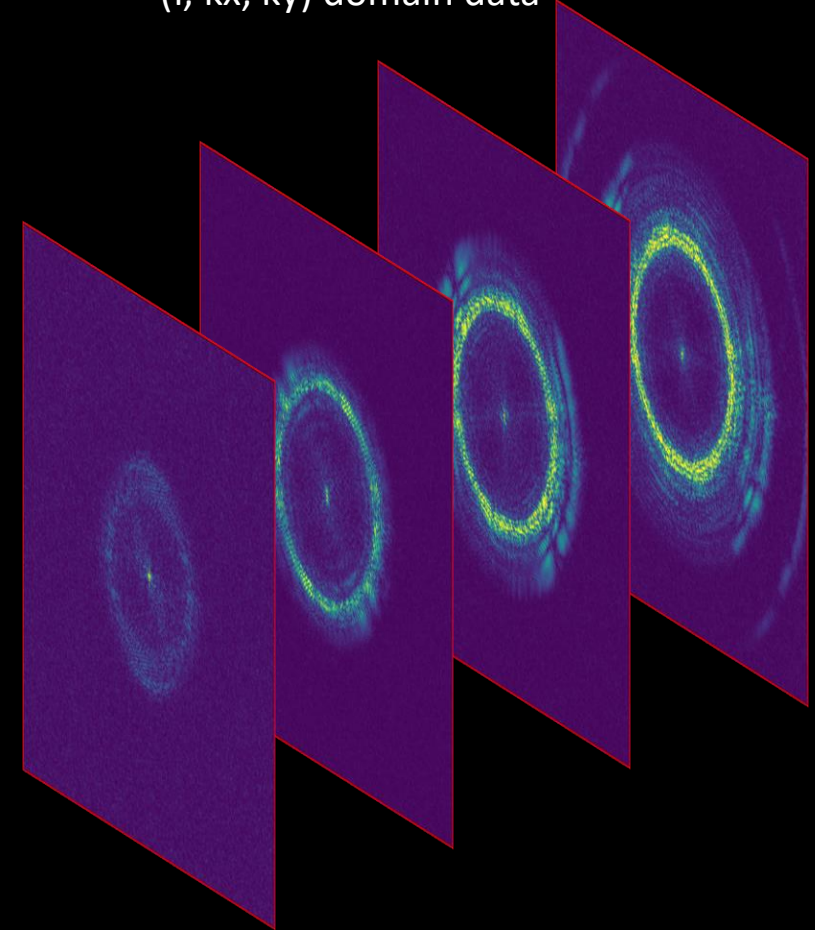
Frequency-Wavenumber Analysis

Filtered data in the spatial-time domain



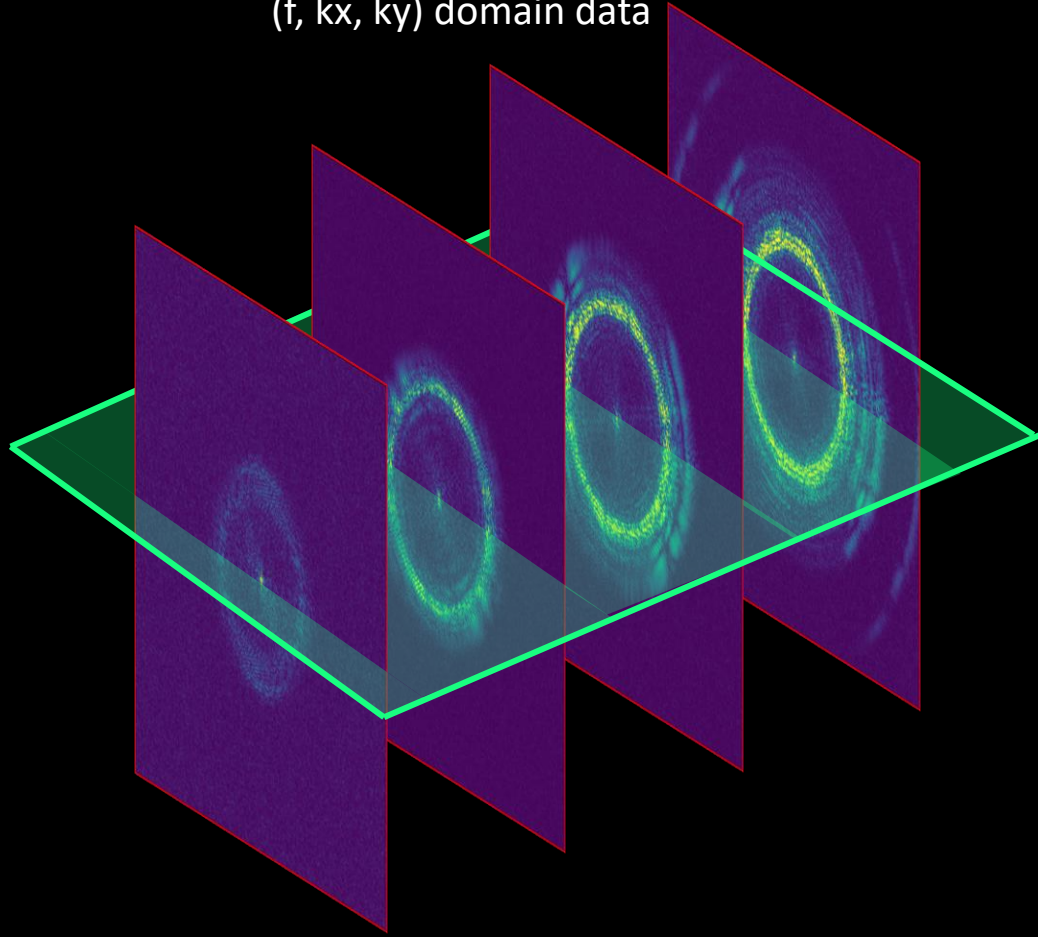
3D FFT

Frequency-wavenumber-wavenumber
(f , k_x , k_y) domain data



Dispersion Curve Representation

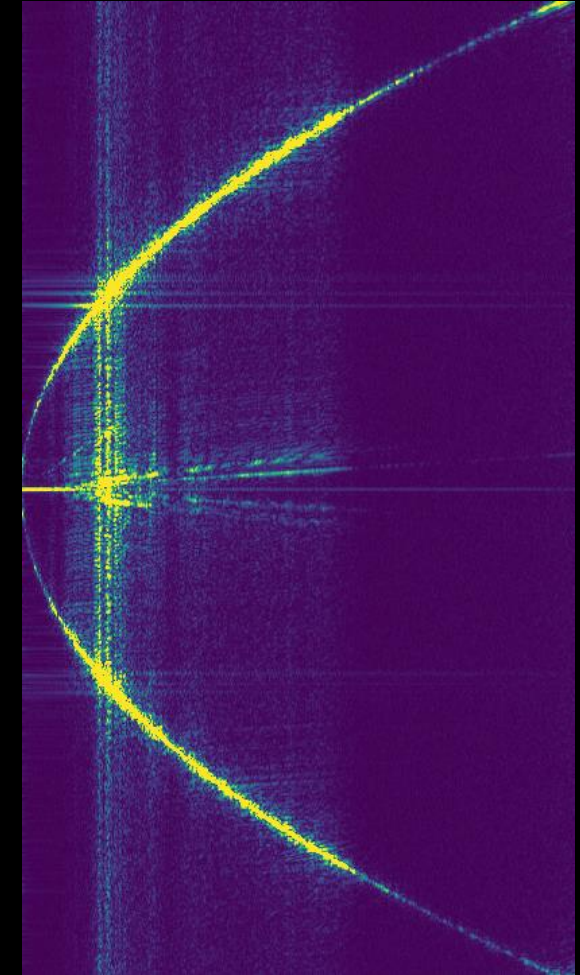
Frequency-wavenumber-wavenumber
(f, kx, ky) domain data



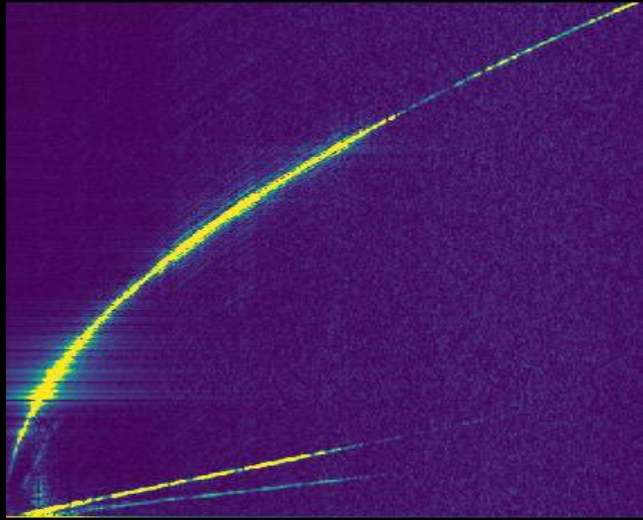
Slice the data to
view dispersion
curve in a single
direction



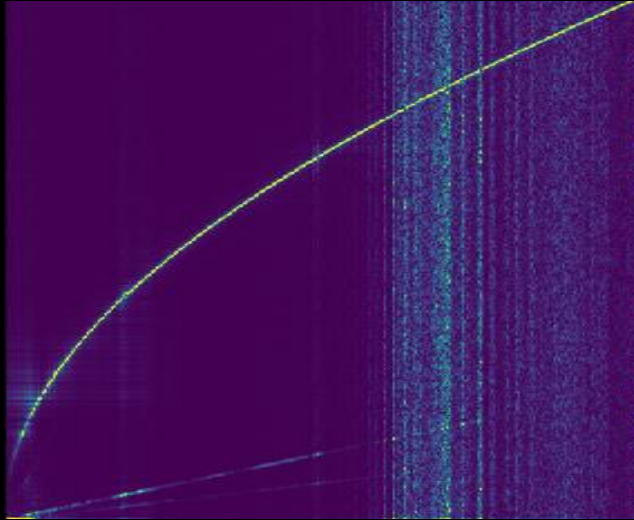
Frequency-wavenumber (f, kx) domain data



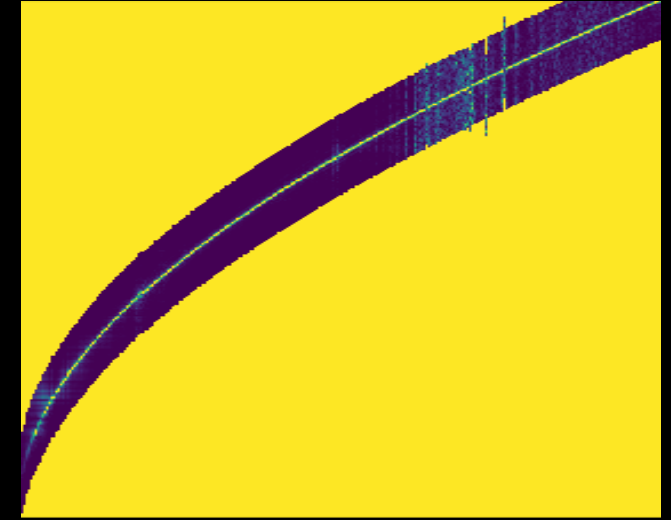
Extracting Lamb Wave Modes



Raw dispersion curve

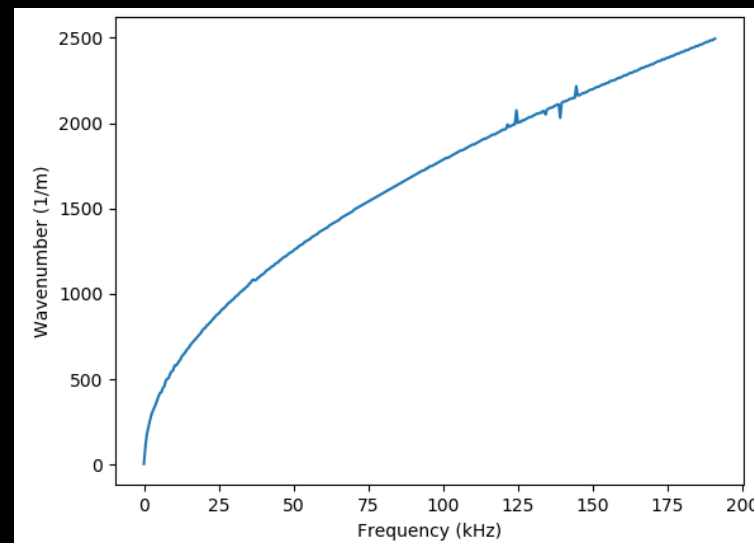


Normalized each frequency bin

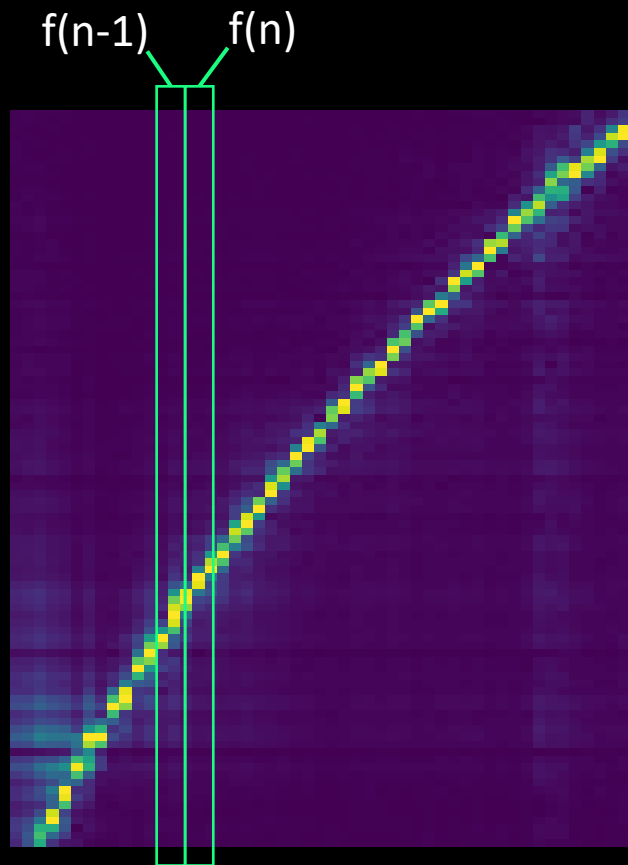


Isolated mode using search algorithm

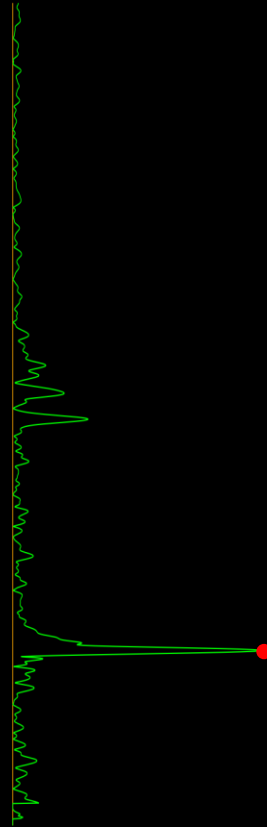
Indexed freq/wavenumber values for local maxima in the isolated mode will output to a line plot of the dispersion curve



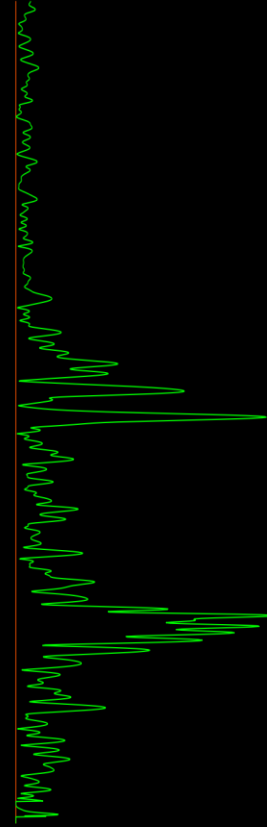
Wave Mode Extraction Technique



Normalized data

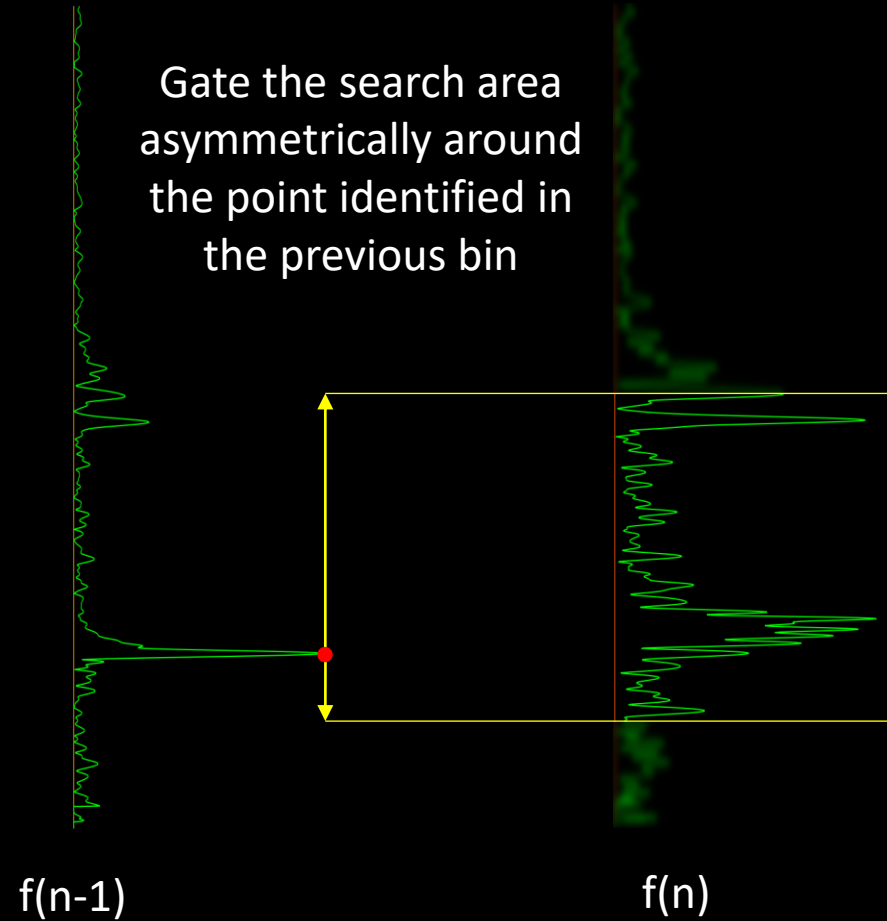
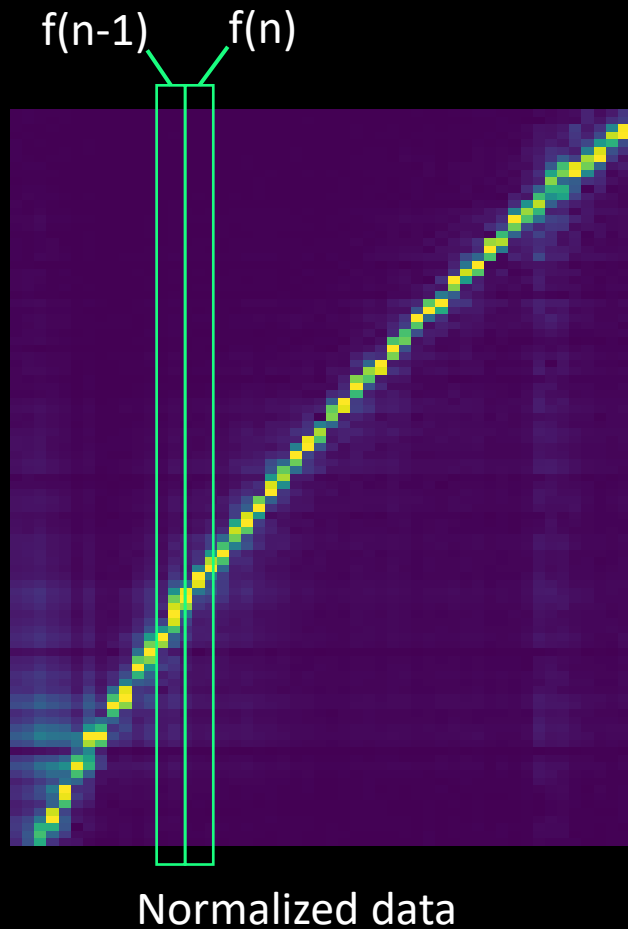


$f(n-1)$
Point on curve identified in
previous frequency bin

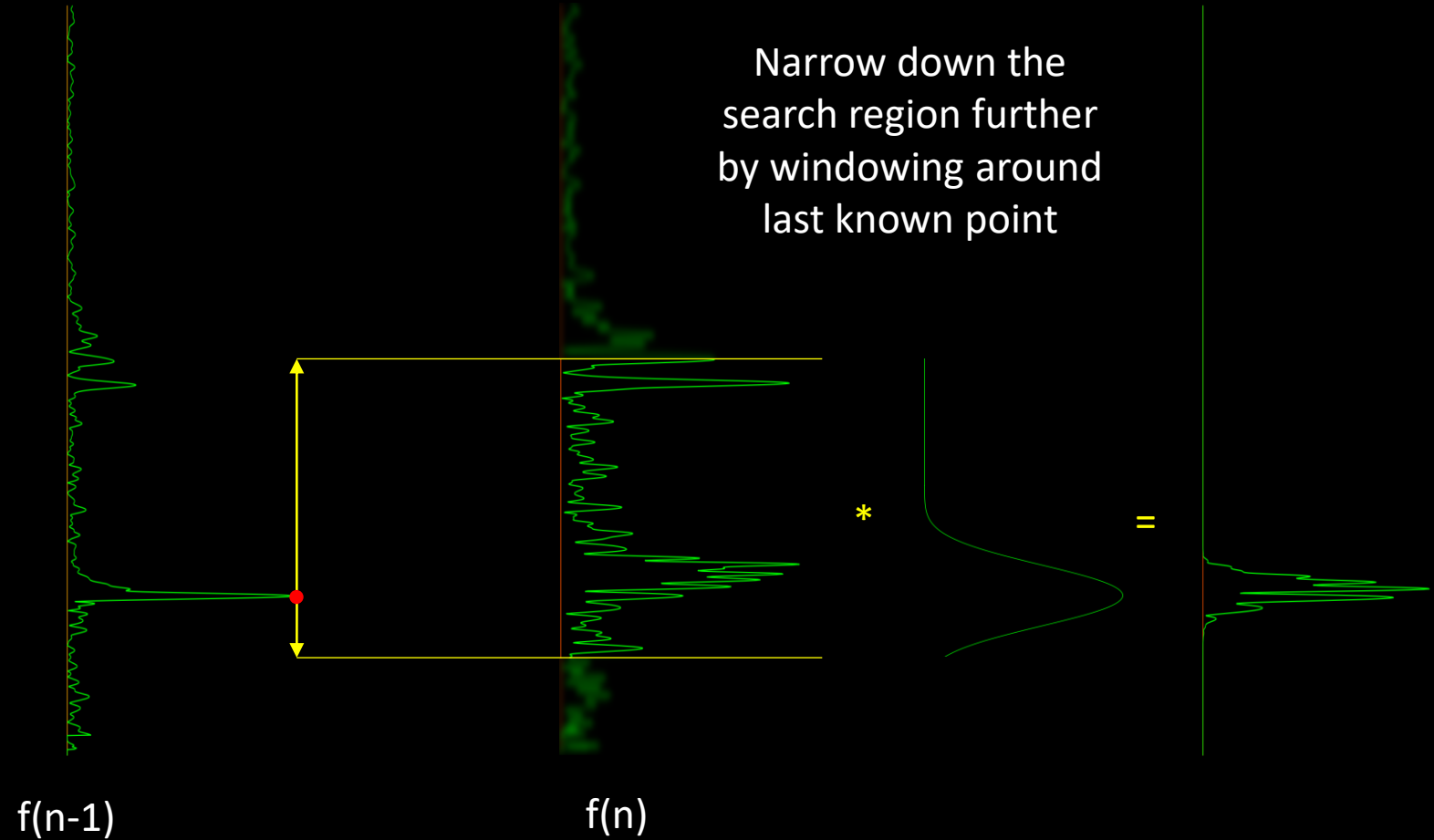
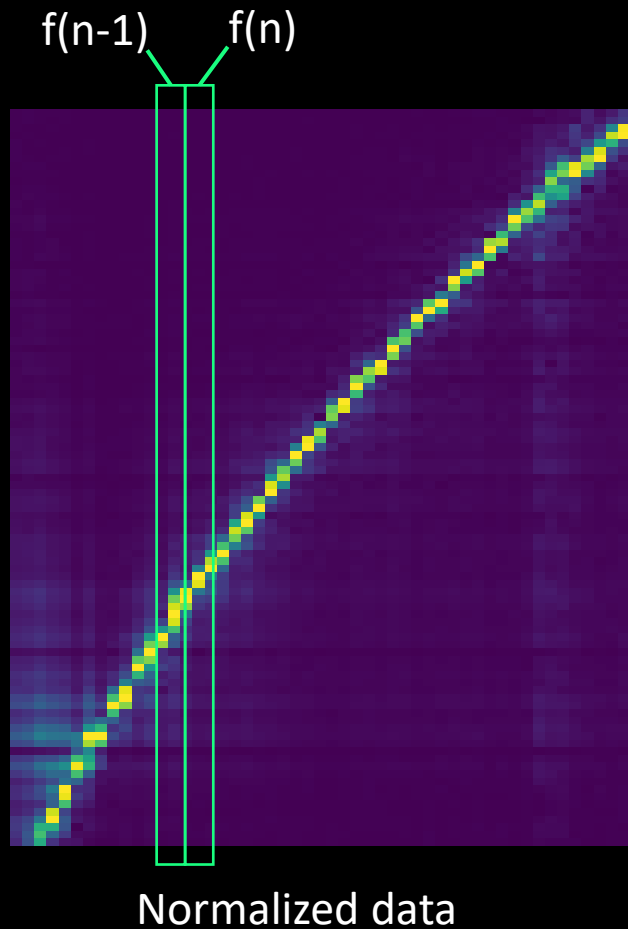


$f(n)$
Frequency bin under
investigation

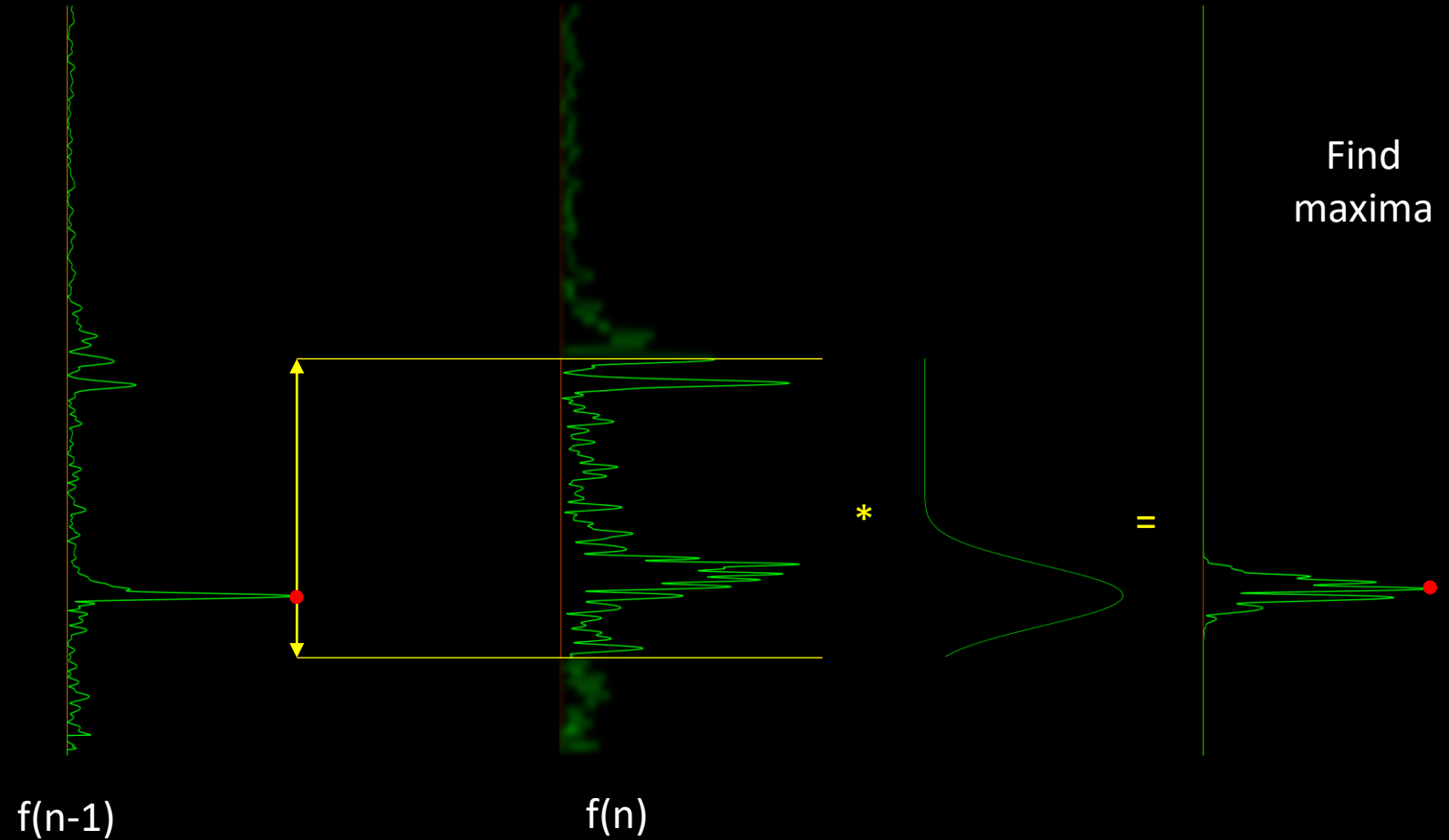
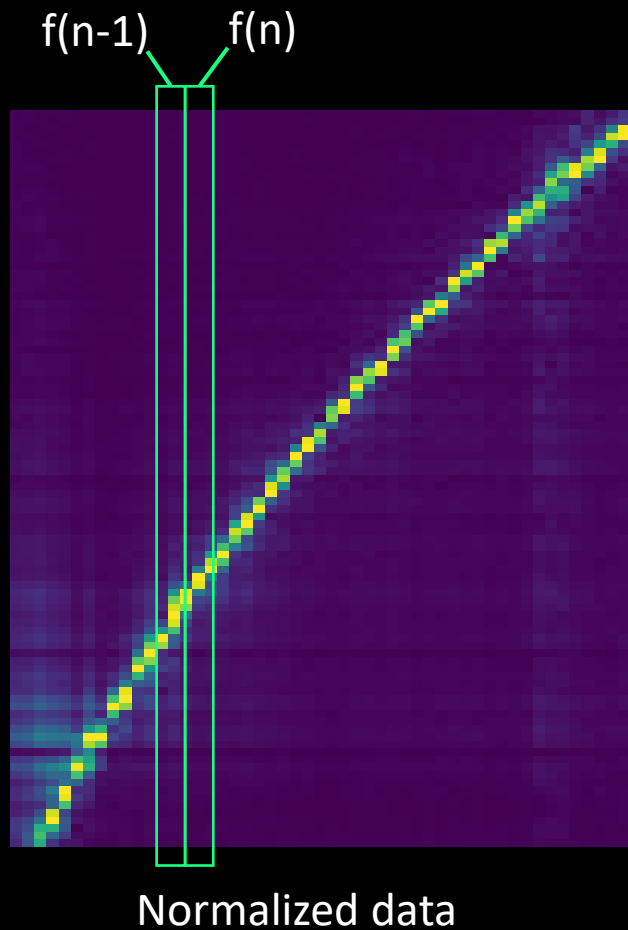
Wave Mode Extraction Technique



Wave Mode Extraction Technique



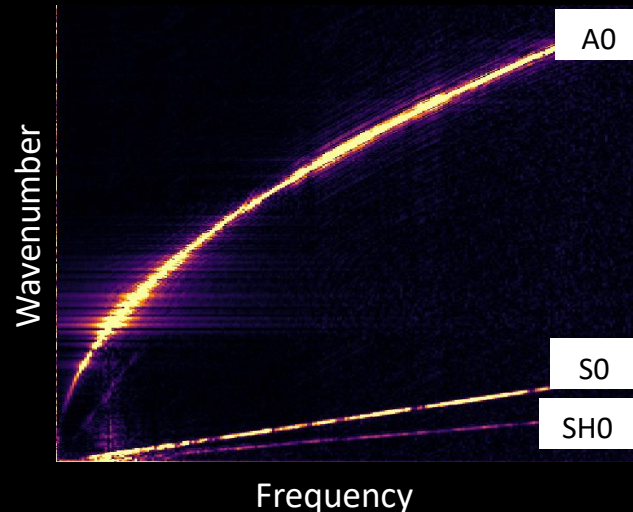
Wave Mode Extraction Technique



Analytical Determination of Material Properties

Extract wavenumber across
frequency spectrum

$$k(\omega)$$



Convert to phase
velocity

$$c = \lambda f$$
$$c = \frac{f}{k}$$

Invert speed-elastic constant
relations

$$c_{SH_0} = \sqrt{\frac{G}{\rho}} \quad c_L = \sqrt{\frac{E}{\rho(1 - \nu^2)}}$$



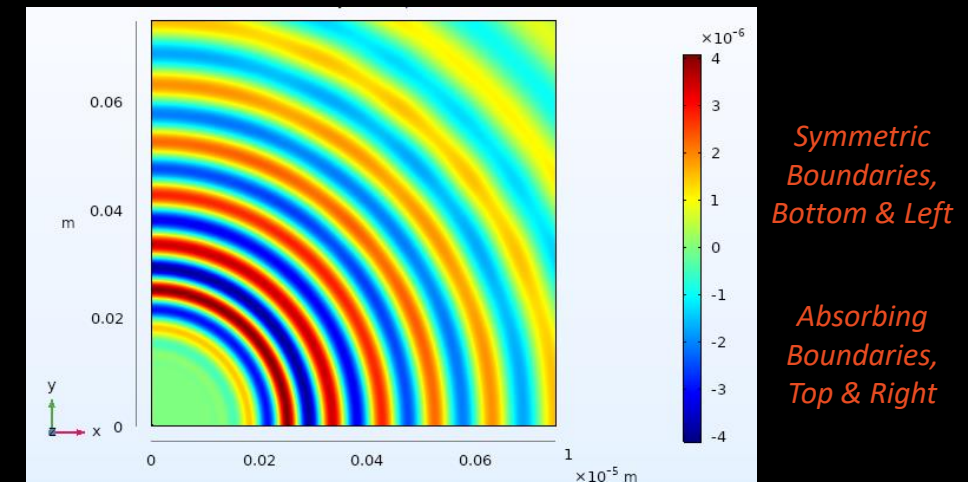
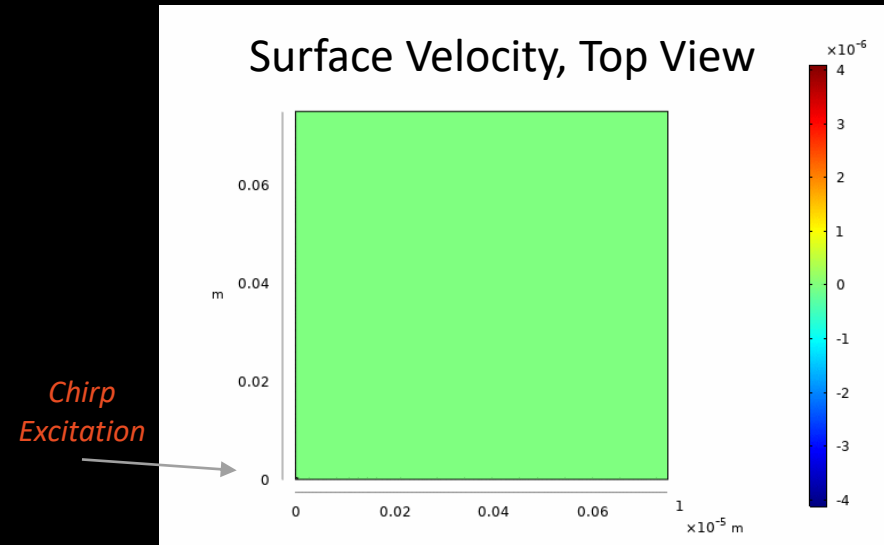
	Measured Properties, via S_0 and SH_0 Modes	Handbook Value ¹	Percent Error
E	121 GPa	115 GPa	4.8%
G	45.0 GPa	43.3 GPa	4.0%

¹Cubberly, W. H. "Metals Handbook 9th Edition, Vol. 2." *American Society for Metals, Metals Park, OH* (1979): 714-831.

FEM Confirmation of Extracted Material Properties

- Confirmation of extracted material properties
 - Import into FEM → Generate wavefield → Extract dispersion curve
- Simulation setup:
 - Broadband excitation, 150-500 kHz chirp
 - Symmetric top/bottom excitation to isolate S0 mode
 - Plate model:
 - length = width = 150 mm
 - Thickness = 25.4 μm
 - 5 quadratic elements/thickness
 - $dx=dy= 0.35 \text{ mm}$
 - ~23 elements per smallest S0 wavelength
- 3D FFT approach to extract dispersion curve
 - Same procedure as experimental extraction

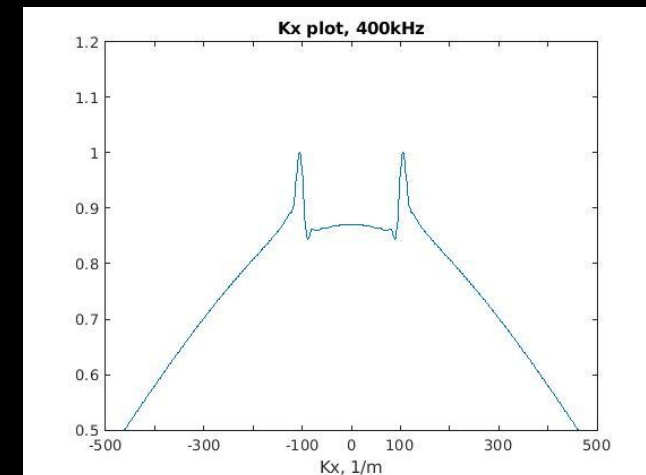
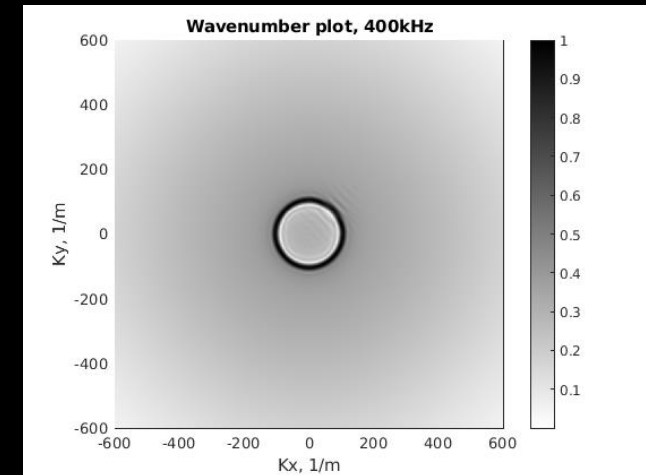
Simulation Results



Simulated Dispersion Curve Results

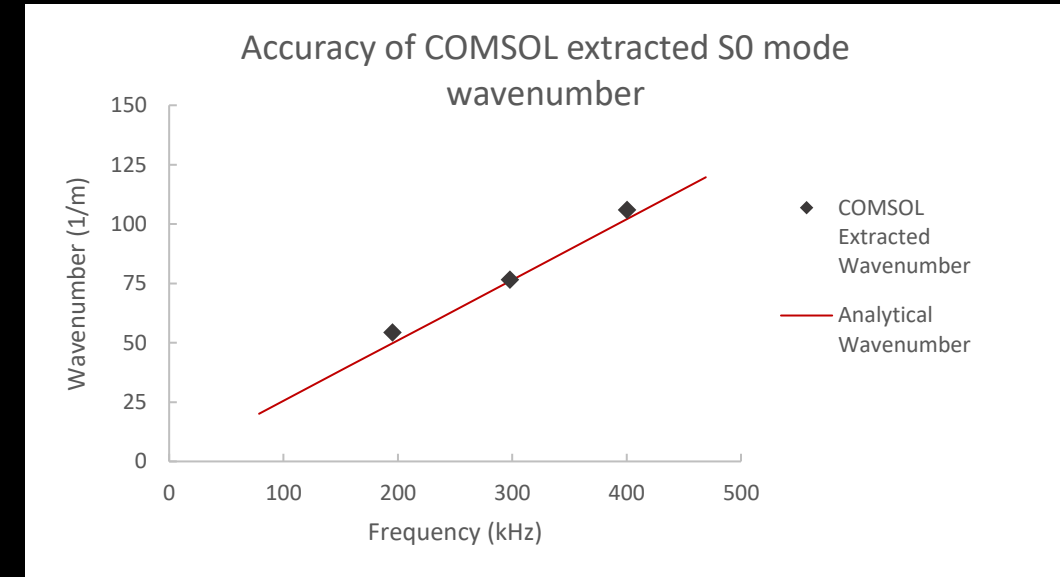
- Extract data from COMSOL simulation files
- Convert COMSOL results into $v(x,y,t)$ data
 - Near-field effects of transducer removed via Tukey window
- Fast Fourier transform to convert data into frequency-wavenumber domain (f, k_x, k_y)
- Wavenumber calculated at a given frequency slice

Wavenumber Plots extracted from COMSOL



Accuracy of Extracted Dispersion Curve Data

- Comparison of empirical wavenumber data to analytical and FEM-extracted results
 - Confirms accuracy of guided-wave extracted material properties
 - Validates dispersion curve extraction approach for both experimental and simulated data
- Accuracy of technique:
 - Experimental extracted wavenumber within ~6% of analytical (dependent on discretization)



Simulation-based dispersion curve extraction important for extension to poroelastic battery materials where analytical approaches have not been developed

Frequency (kHz)	Simulated Wavenumber (1/m)	Analytical Wavenumber (1/m)	Percent Error
195.3	51.1	54.4	6.1 %
297.9	77.3	76.6	-0.8 %
400.4	102.1	106.0	3.7 %

Conclusions and Future Work

- Guided wave detection and dispersion curve extraction on thin foil
- Material property estimation using longitudinal and shear horizontal modes
 - Reasonable estimates of material properties ($\sim 5\%$ error) for Cu 110 specimen
 - Technique insensitive to thickness tolerance and imperfections in foil (e.g. wrinkles)
- Dispersion curves simulated in COMSOL with measured properties, accuracy depends on discretization (higher error at smaller wavelengths)
 - Benefit of using finite element (FEM) simulation when moving onto more complex material models where analytical dispersion curve theories have not been developed

Future Work:

- Extension of technique to poroelastic and isotropic tri-layer components
- Use of measured/inferred properties in battery ultrasound models to support inspection/monitoring under different wear and defect conditions