Lamb Wave Nondestructive Evaluation and Imaging on Plate-Like Structures

Zhaoyun Ma

Ph.D. Comprehensive Exam Defense

08/05/2019

Outline

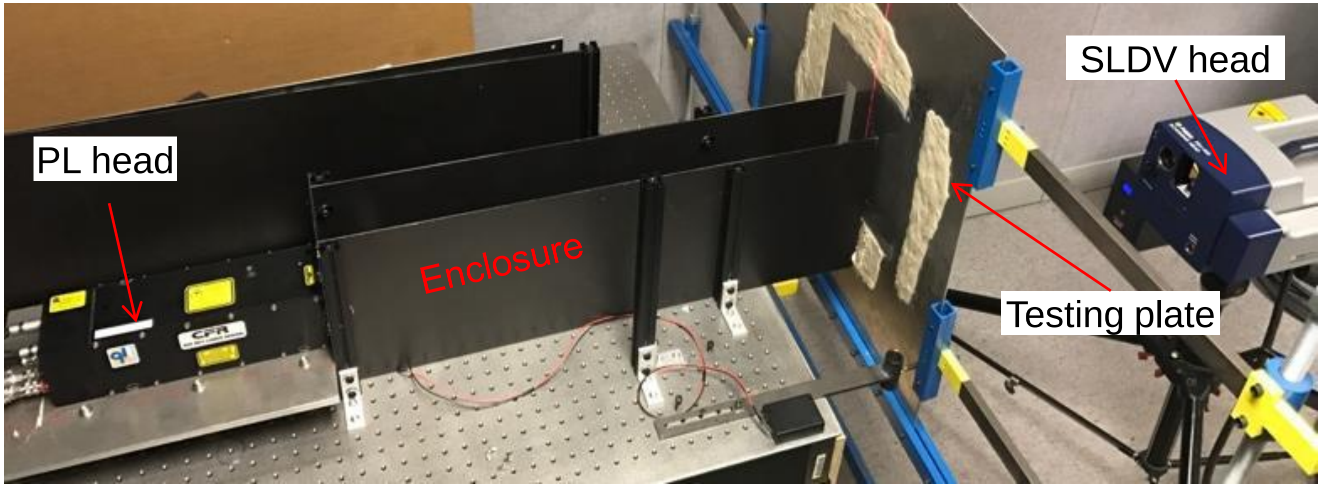
- Research motivation and objectives
- State of the art
- Proposed work
  - Task 1: Lamb wave fundamental study
  - Task 2: Partial non-contact piezoelectric transducer-scanning laser Doppler vibrometer (PZT-SLDV) Lamb wave based methodology
  - Task 3: Fully non-contact pulsed laser-scanning laser Doppler vibrometer (PL-SLDV) laser system
  - Task 4: Applications to various nondestructive evaluation/structural health monitoring (NDE/SHM) paradigms
- Summary, timeline, and expected contributions

Task 3: Fully non-contact PL-SLDV laser system development

Subtask 3.1: PL excitation integration with SLDV

- Actuation: Quantel CFR400 Nd:YAG pulsed laser (Q-switch)
- Sensing: Polytec PSV-400 SLDV system
- PL and SLDV heads
  - are placed on each side of the testing specimen
  - are normal to the specimen

PL-SLDV system

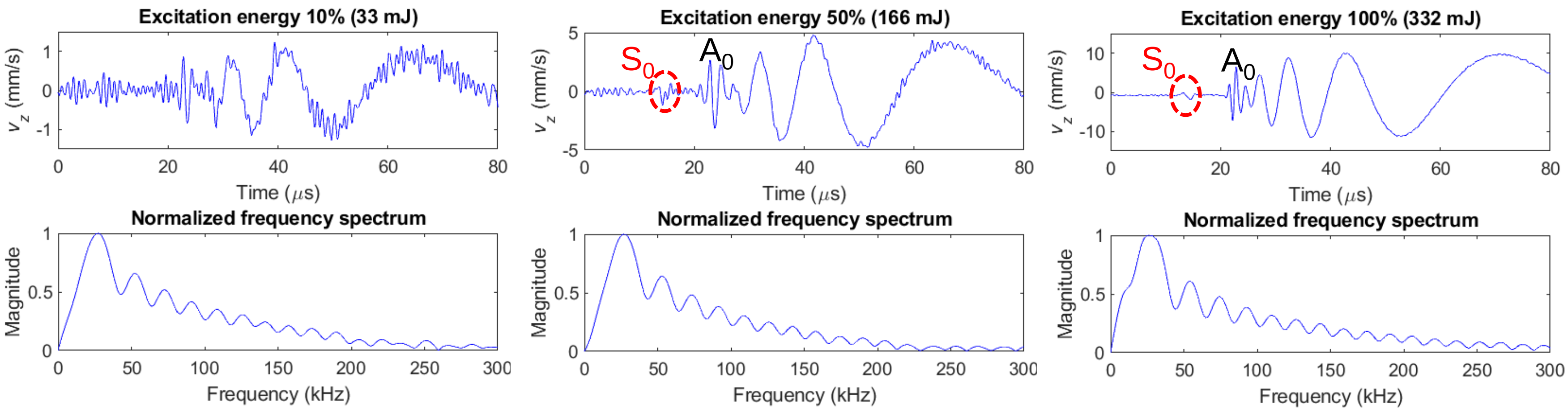


(Ma and Yu, 2019)

Optimal Lamb wave excitation

- Specimen: 1-mm aluminum plate
- Actuation: PL excitation with 3% to 100% (10-332 mJ) of the full energy
- Sensing: SLDV at 60 mm away from the excitation with sampling rate 10.24 MHz

Results at selected excitation energy: 33, 166, and 332 mJ

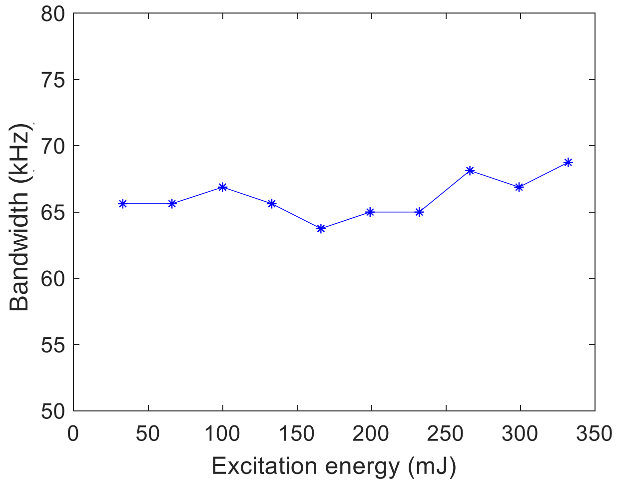


(Ma and Yu, 2019)

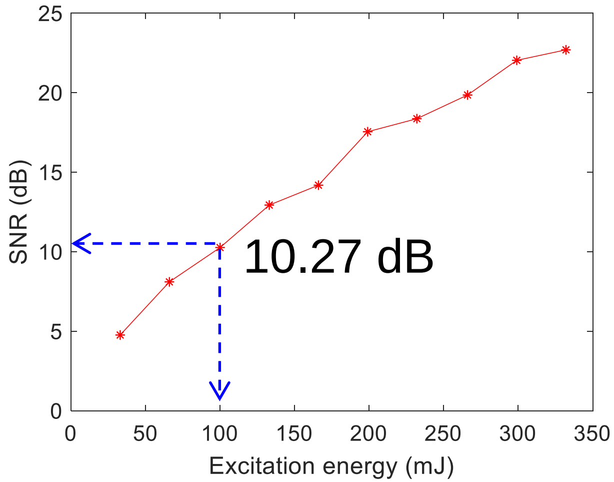
Signal quality evaluation

- The signal quality are evaluated by
  - Signal-to-noise ratio (SNR)
  - Bandwidth of full width at half maximum (FWHM)

Bandwidth



SNR



- Bandwidth does not change significantly
- SNR increases with the increase of excitation energy

(Ma and Yu, 2019)

Surface enhancement study

- Three surface conditions at 60 mm away from the excitation
  - Raw surface (SC-1)
  - 0.7 mm thick aluminum foil (SC-2)
  - 0.7 mm thick copper foil (SC-3)

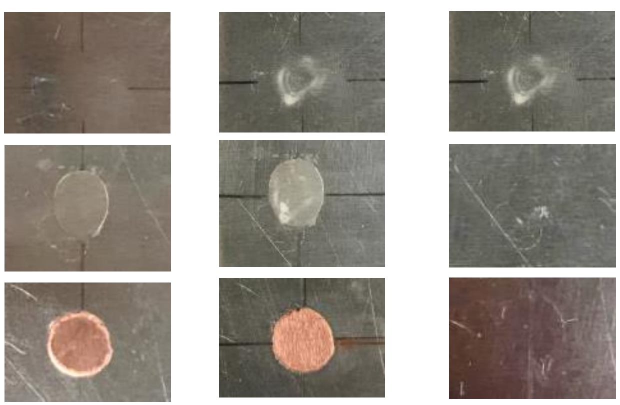
Surface conditions

Before | After | After removal

SC-1

SC-2

SC-3



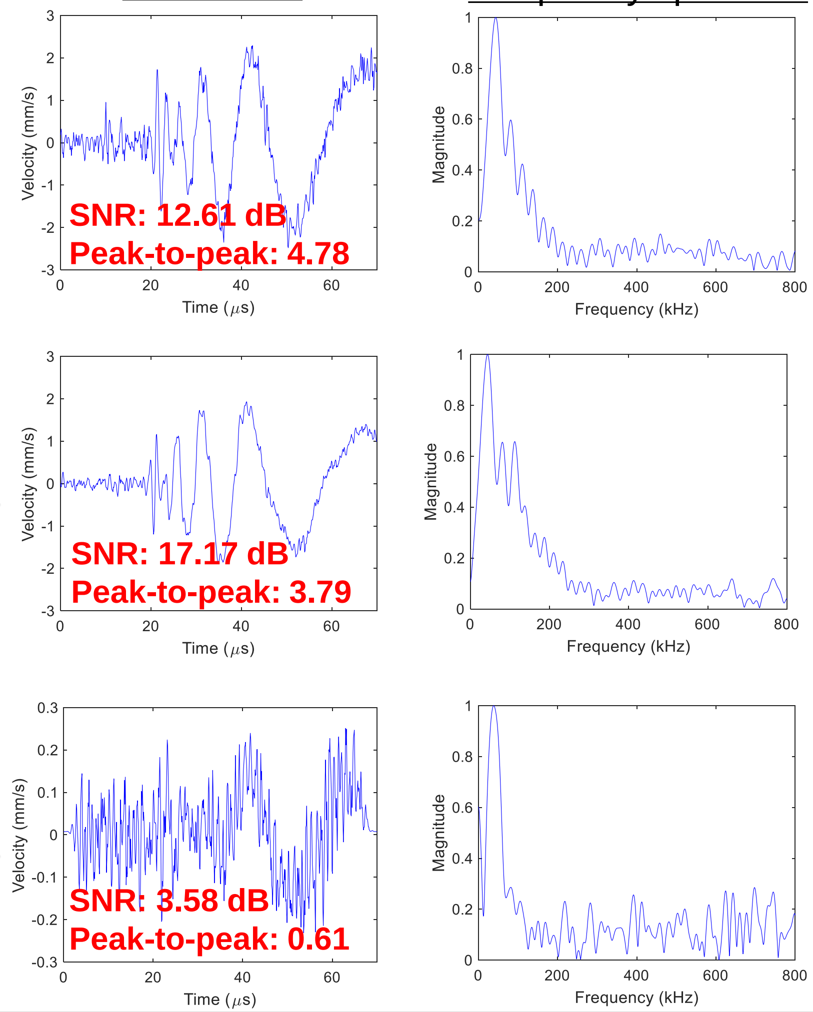
Signal quality evaluation

waveforms | Frequency spectrum

SC-1

SC-2

SC-3



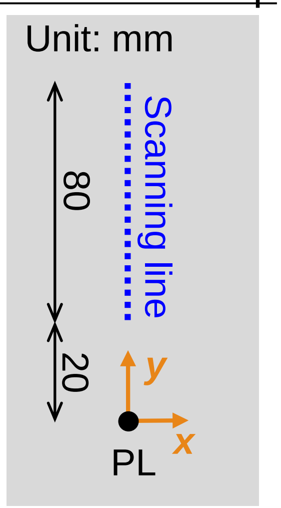
UNIVERSITY OF SOUTH CAROLINA

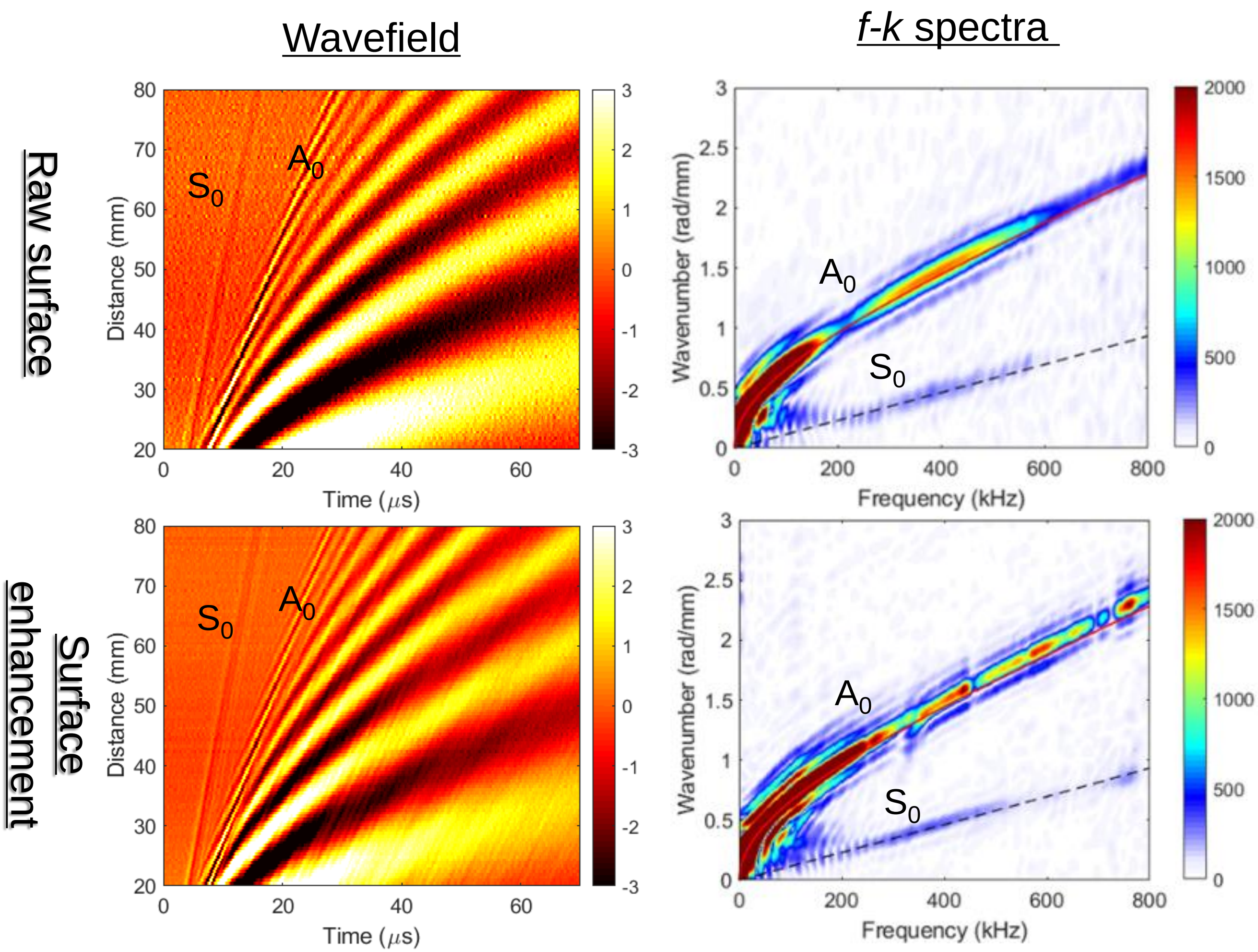
VSHM

Characterization of PL Lamb wave

- PL excitation: 100 mJ with repetition rate 20 Hz
- Surface enhancement: 0.7 mm thick aluminum foil

Line scan setup





(Ma and Yu, 2019)

Subtask 3.2: Proof-of-concept defect detection

- Specimen: 1 mm aluminum plates
  - Pristine
  - Defect plates with simulated defect at *y* = 70 mm
    - Surface bonded quartz rod
    - Simulated crack (machine milled through thickness notch)
- Inspection
  - 1D line inspection
  - 2D area inspection

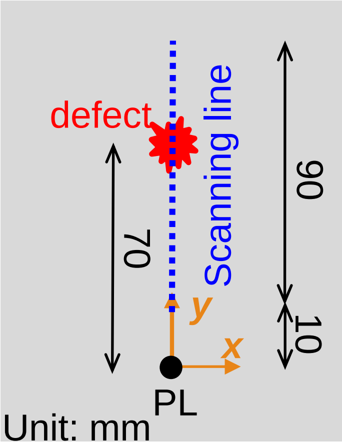
<u>Surface bonded quartz</u>

- 10 mm thickness
- 10 mm diameter

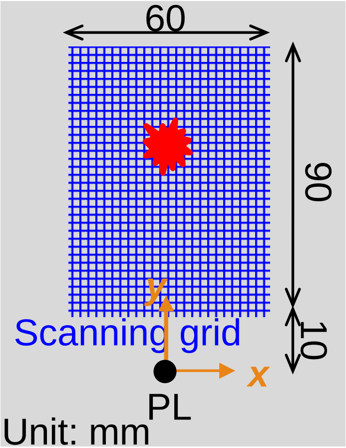
<u>Simulated crack</u>

- 10 mm long
- 0.5 mm width

<u>1D inspection schematic</u>



<u>2D inspection schematic</u>



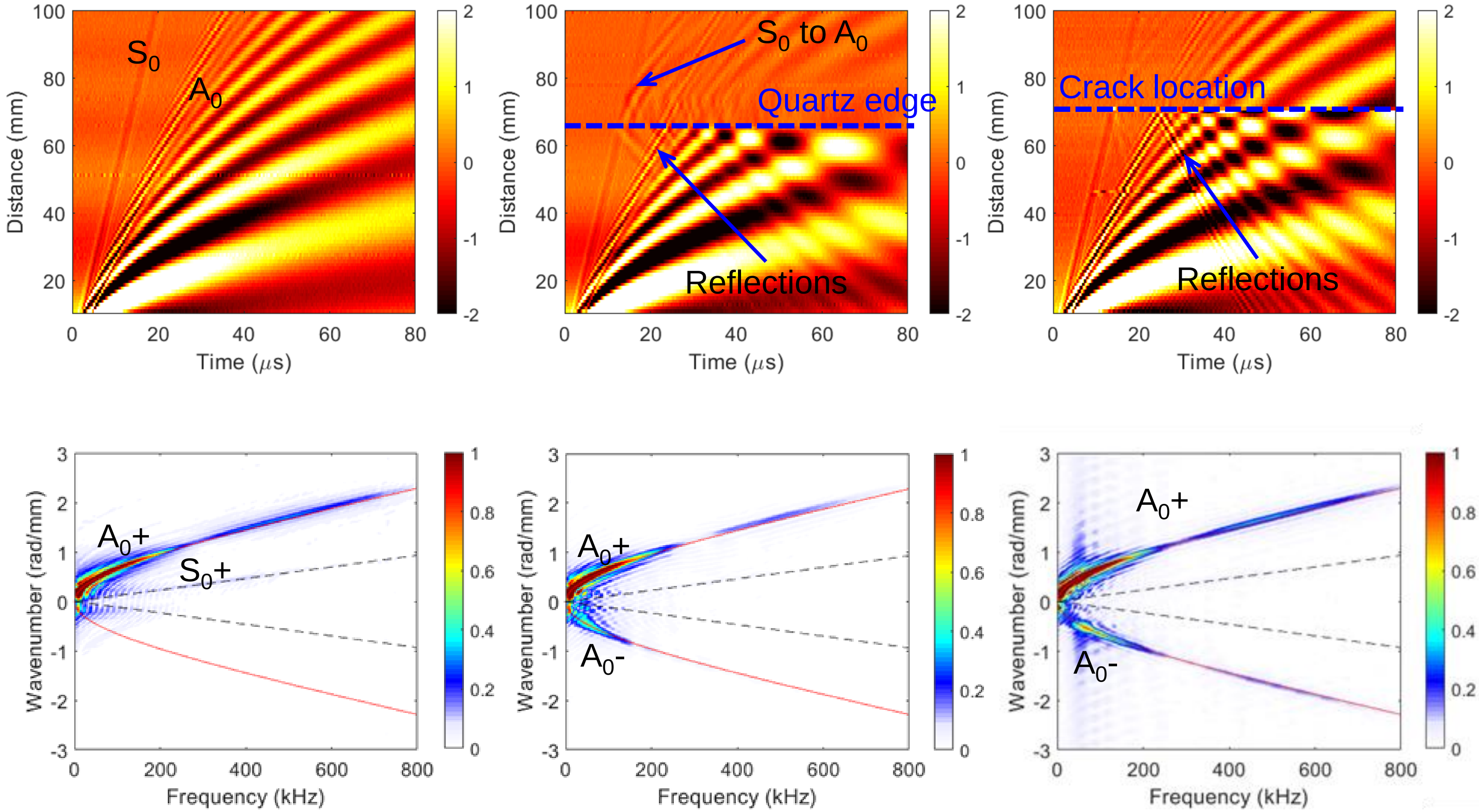
(Ma and Yu, 2019)

1D inspection results

Pristine plate | Quartz plate | Crack plate

Wavefield

f-k spectra

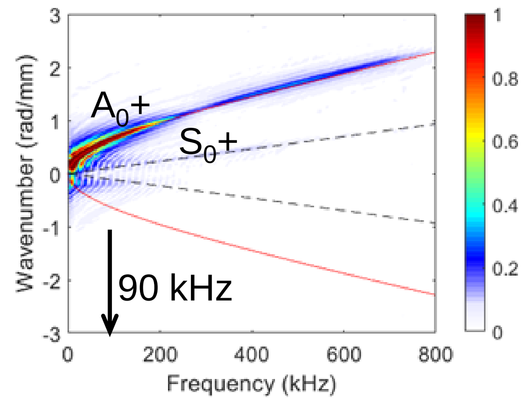


(Ma and Yu, 2019)

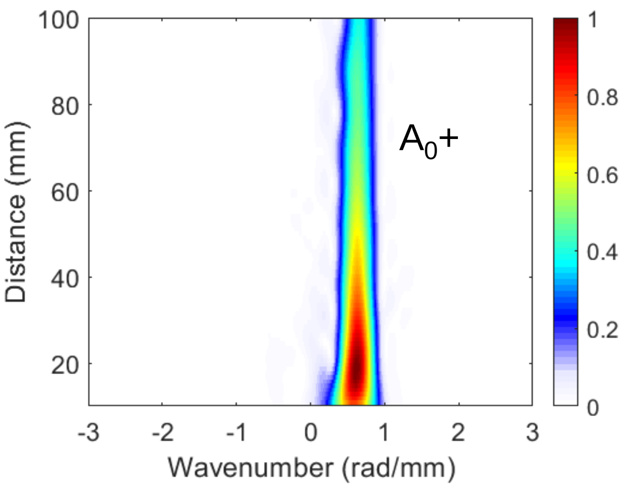
Short space-wavenumber (*x-k*) analysis

- Interested frequency: 90 kHz
  - With A0 dominate (wavenumber 0.62 rad/mm)

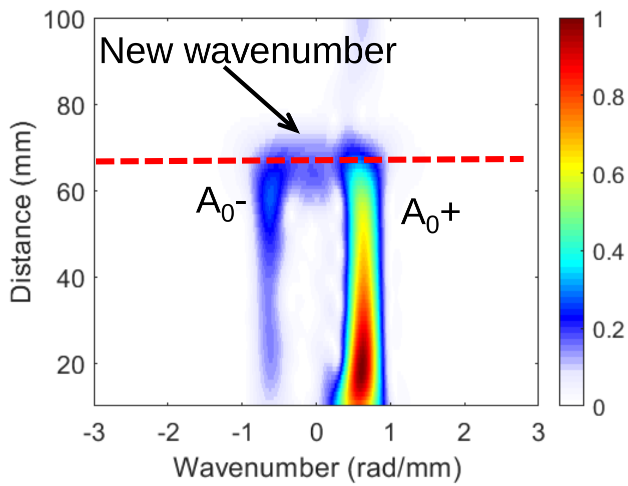
f-k spectra



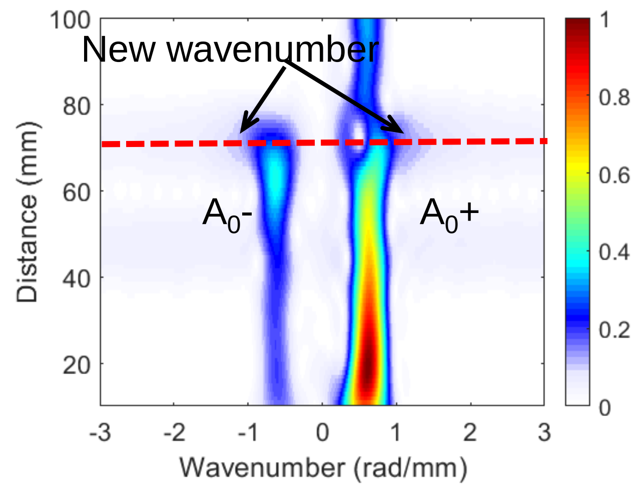
Pristine plate



Quartz plate

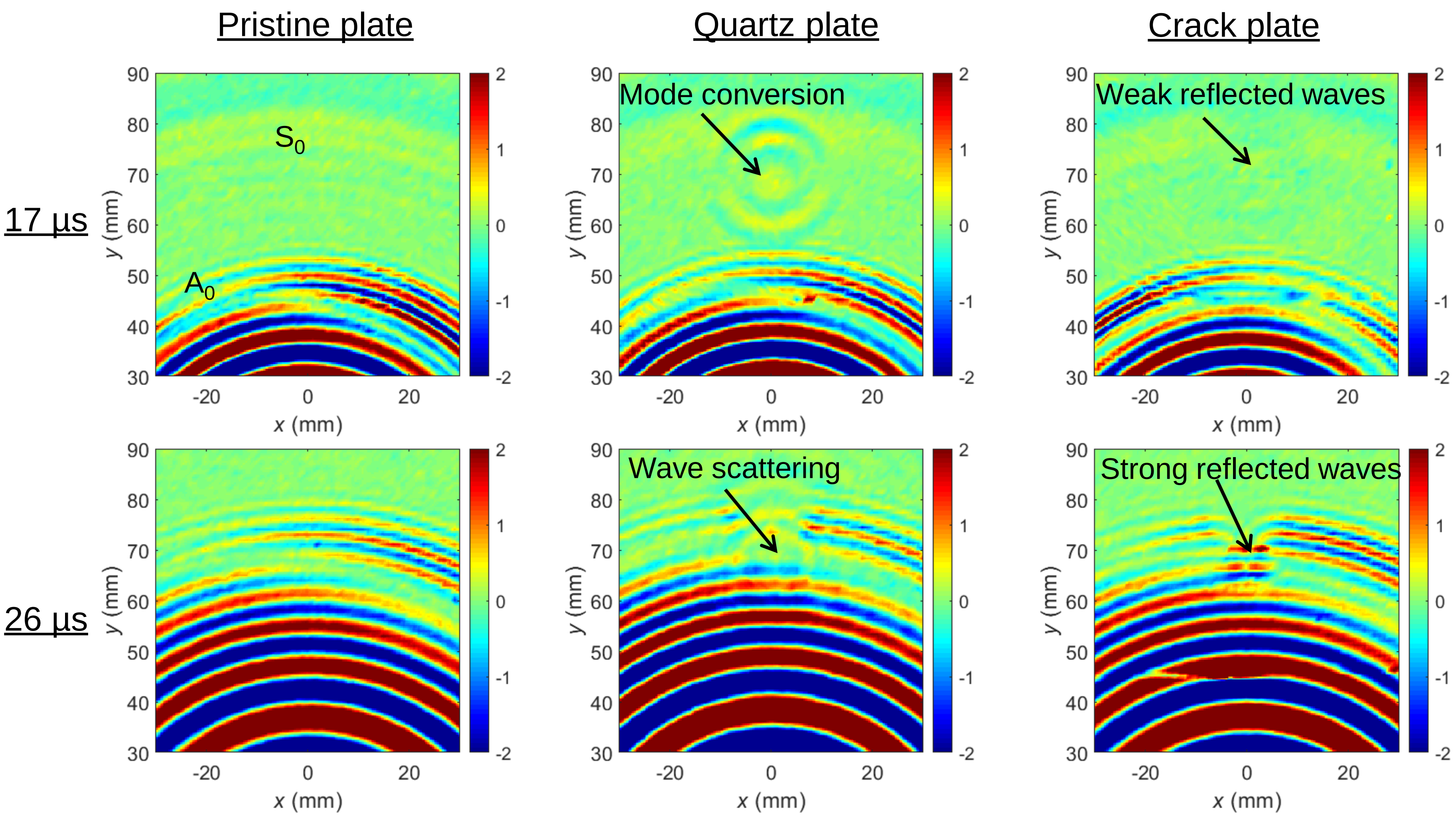


Crack plate



(Ma and Yu, 2019)

2D Wave interaction with defects

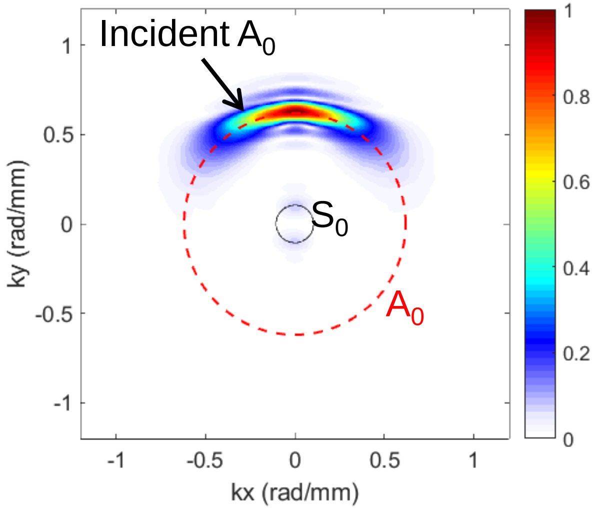


(Ma and Yu, 2019)

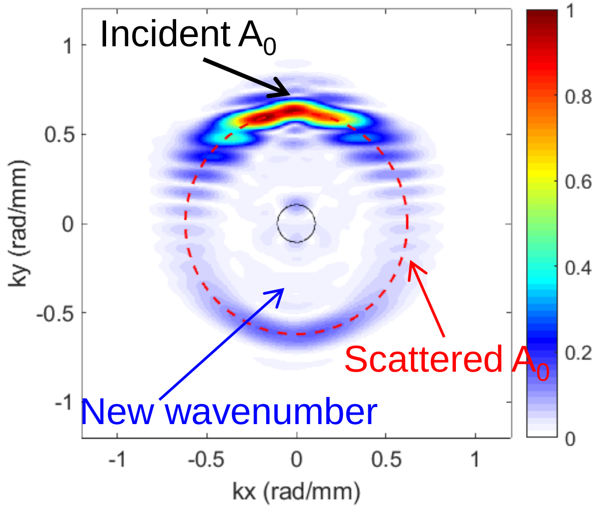
Wavenumber analysis

- Interested frequency: 90 kHz

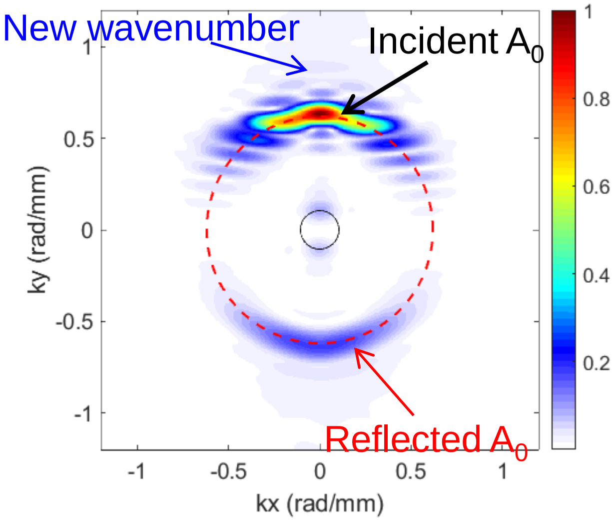
<u>Pristine plate</u>



<u>Quartz plate</u>



<u>Crack plate</u>



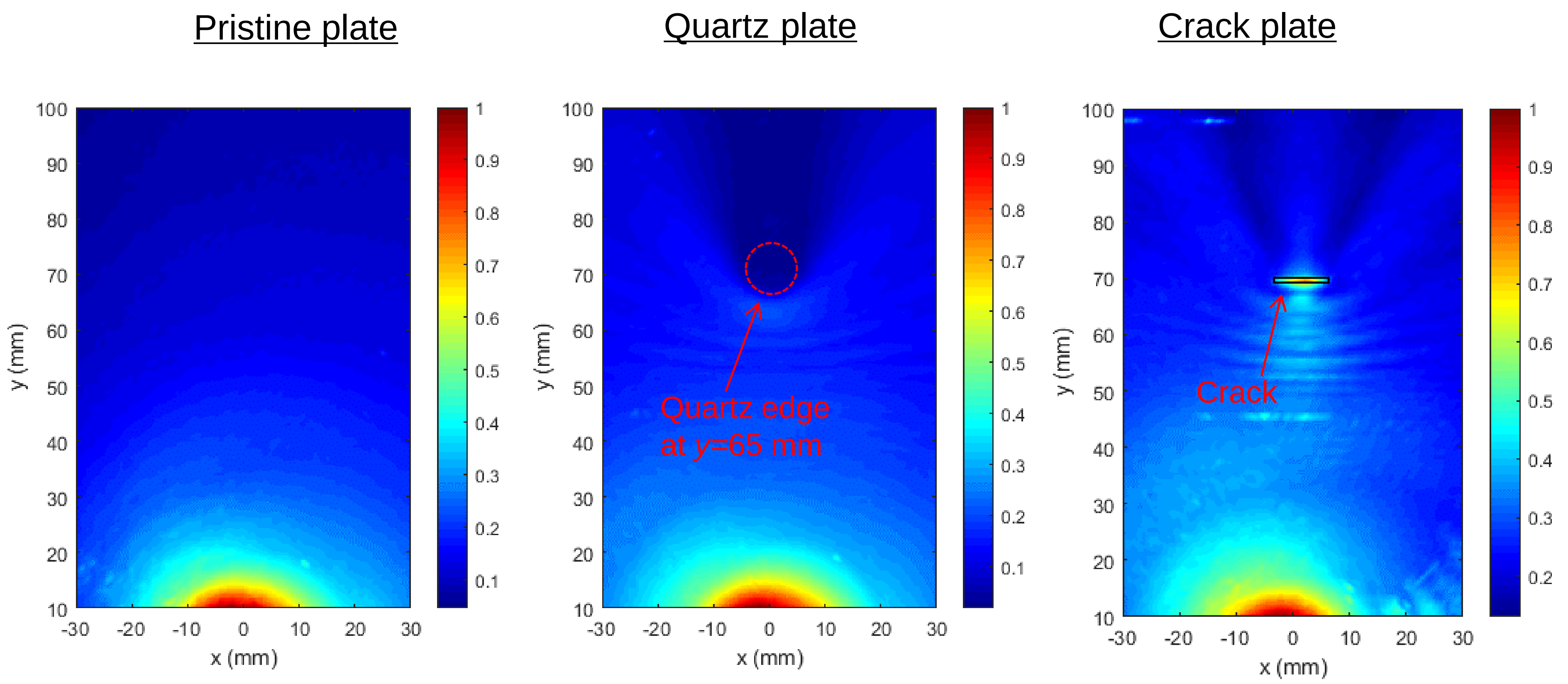
- Only incident A_0: wavenumber 0.62 rad/mm

- Incident A_0
- Scattered A_0
- New wavenumbers (defect induced, <0.62 rad/mm)

- Incident A_0
- Reflected A_0
- New wavenumbers (defect induced, >0.62 rad/mm)

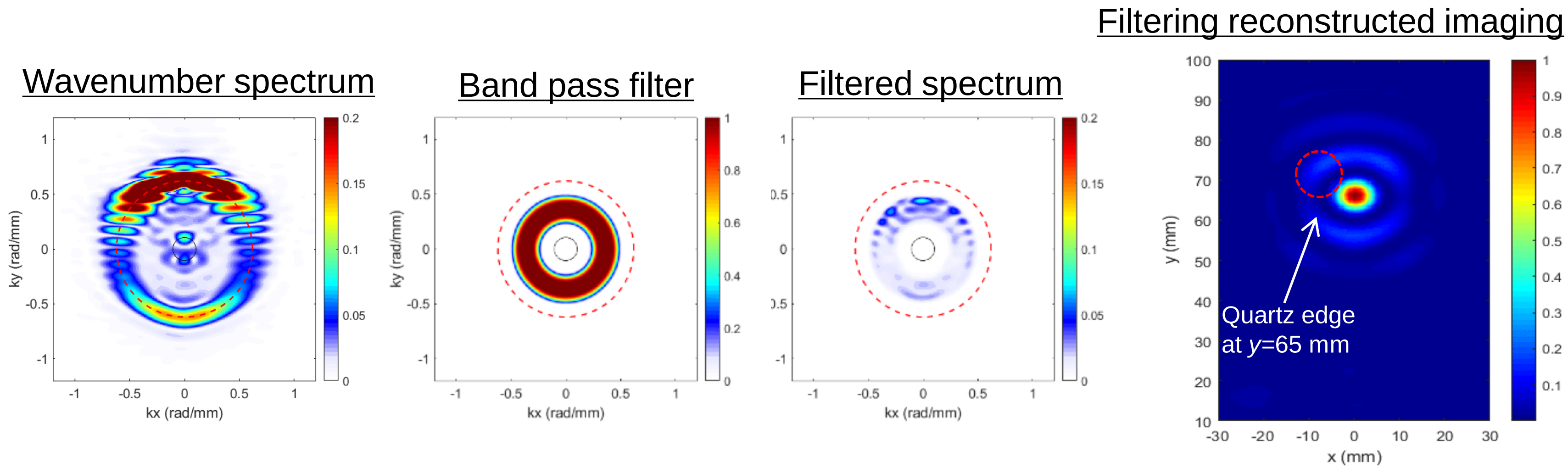
(Ma and Yu, 2019)

Wavefield Imaging

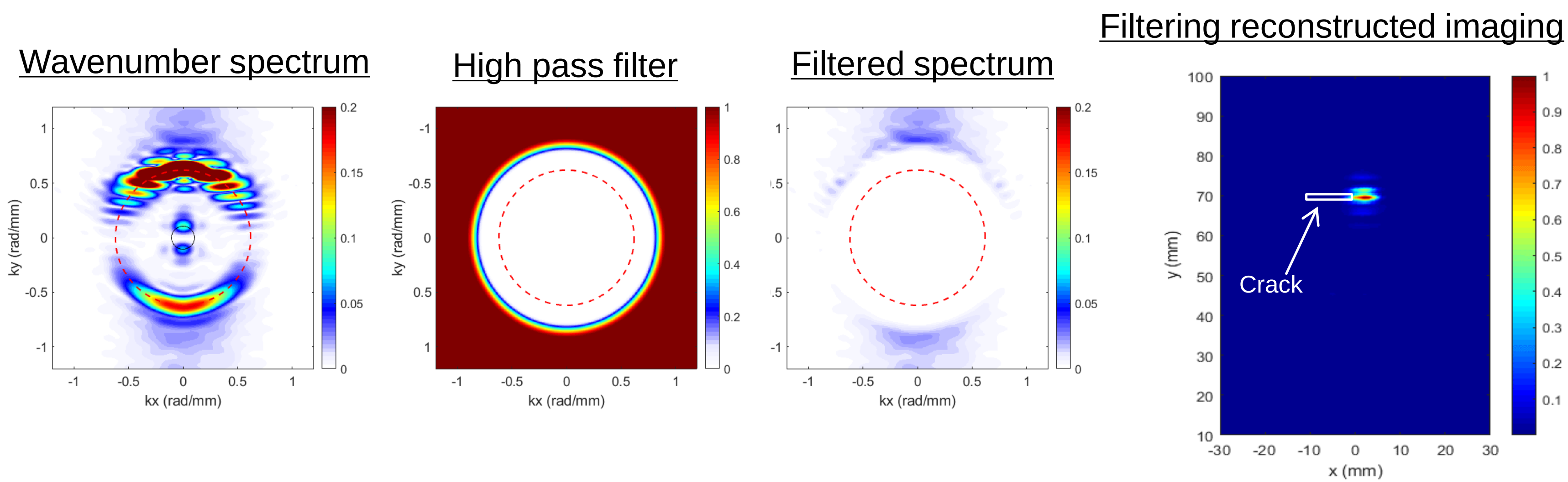


Filtering reconstruction imaging

Quartz plate

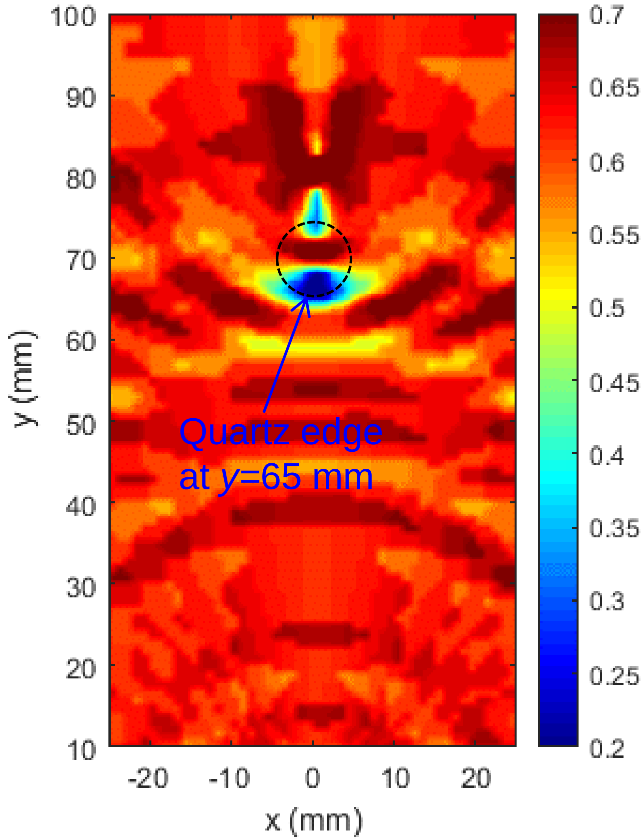


Crack plate

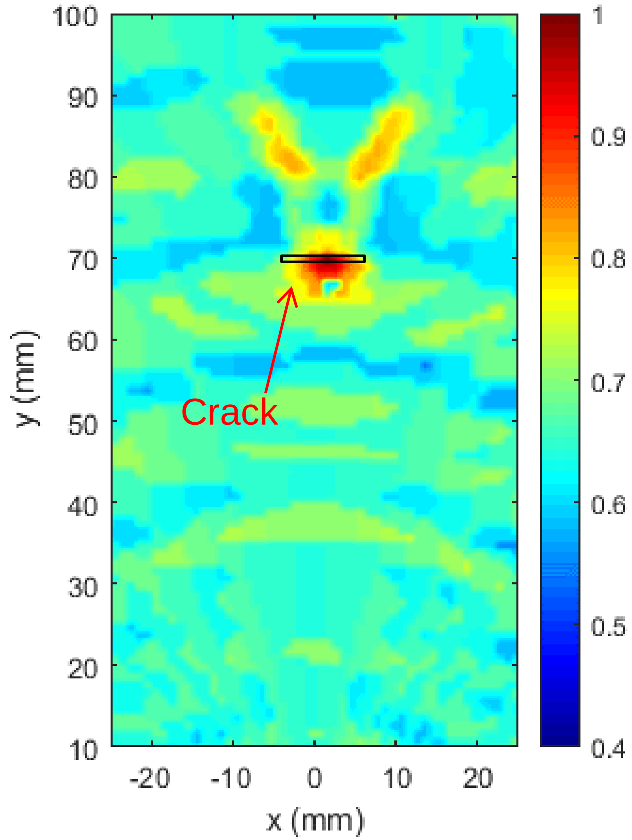


Wavenumber imaging

Quartz plate



Crack plate



Progress of Task 3

<u>100% of Task 3 has been completed</u>

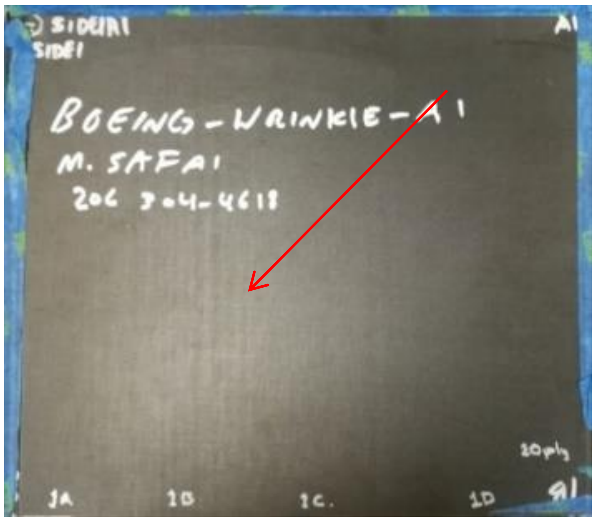
- PL-SLDV non-contact system development
  - Excitation energy vs. signal quality
  - Surface enhancement study
  - Lamb wave characterization
- Proof-of-concept defect detection
  - 1D inspection and 2D inspection
  - Defect further evaluation

Task 4: Applications to various NDE/SHM paradigms

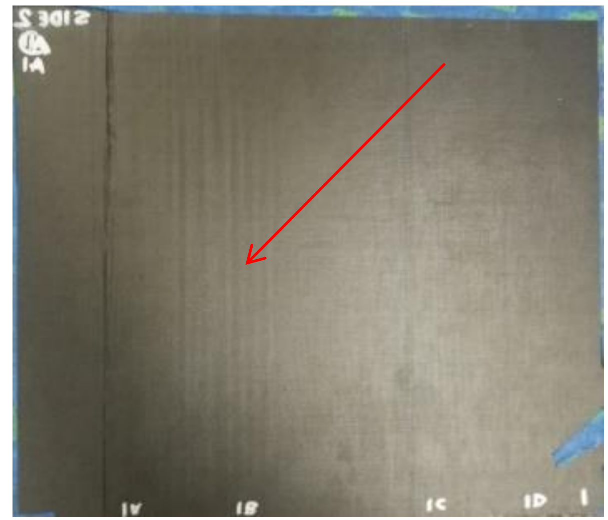
Subtask 4.1: Inspection with PZT-SLDV system

- Wrinkle inspection

Top view (side-1)



Bottom view (side-2)

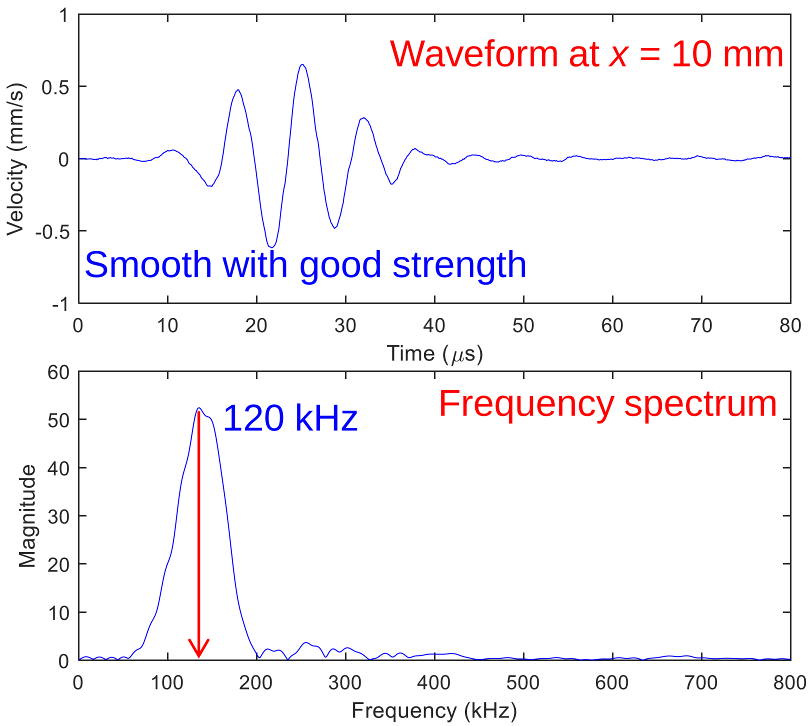


Side view

Non-invasive PZT-SLDV setup

- Non-invasive PZT-SLDV system
  - Simply Balanced™ honey as couplant for PZT actuation
  - Albedo 100 wipe-off reflective spray as SLDV enhancement

Signal acquired using the non-invasive system



Honey

https://www.target.com

Reflective spray

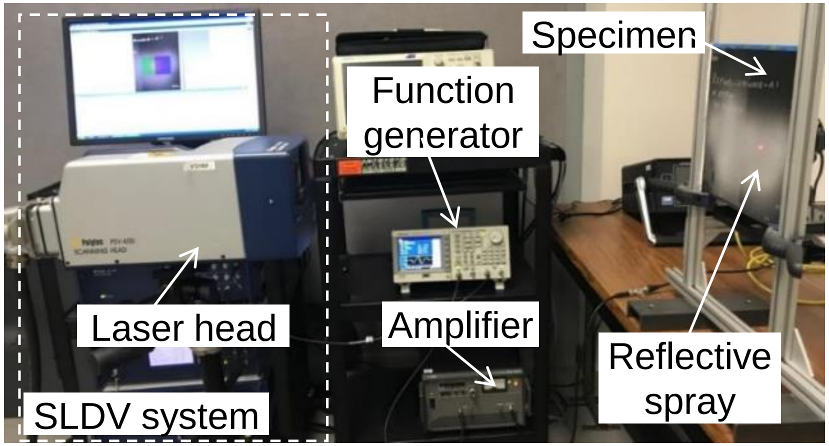
https://www.albedo100us.com/

SLDV signal strength indicator

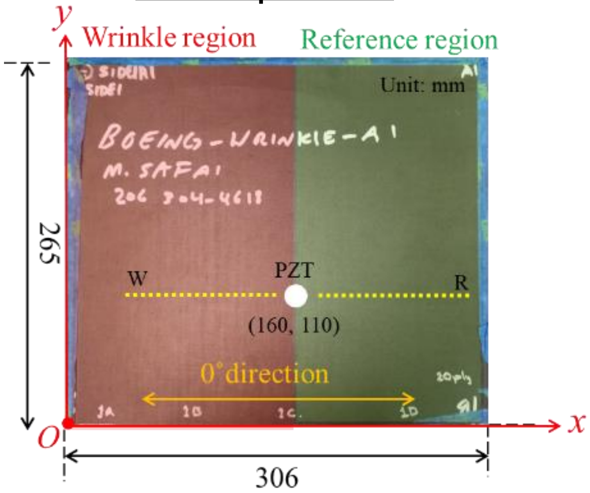
Experimental setup

- Specimen: 20-ply CFRP plate with unknown material properties
- Actuation: 3-count toneburst at 50 V_{pp}
  - Inspection frequency selection: 120 and 210 kHz
- Sensing: 1D and 2D inspection with 1 mm spatial resolution

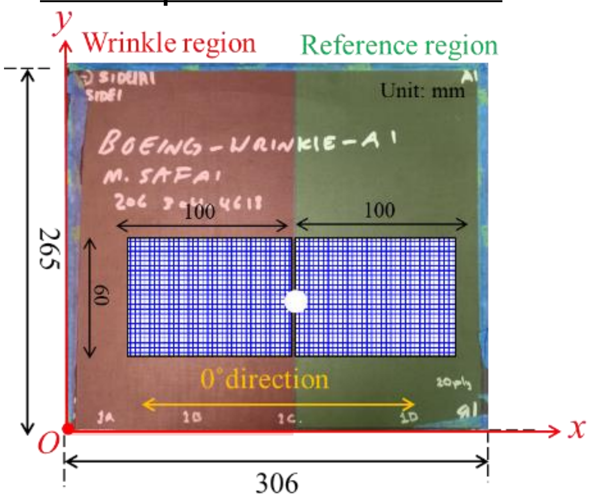
Experimental setup



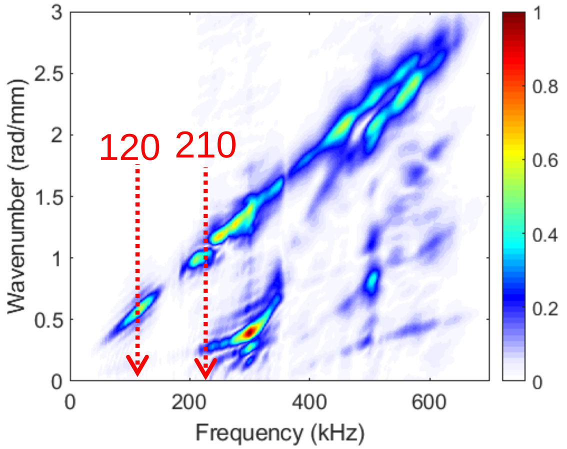
1D inspection



2D inspection schematic

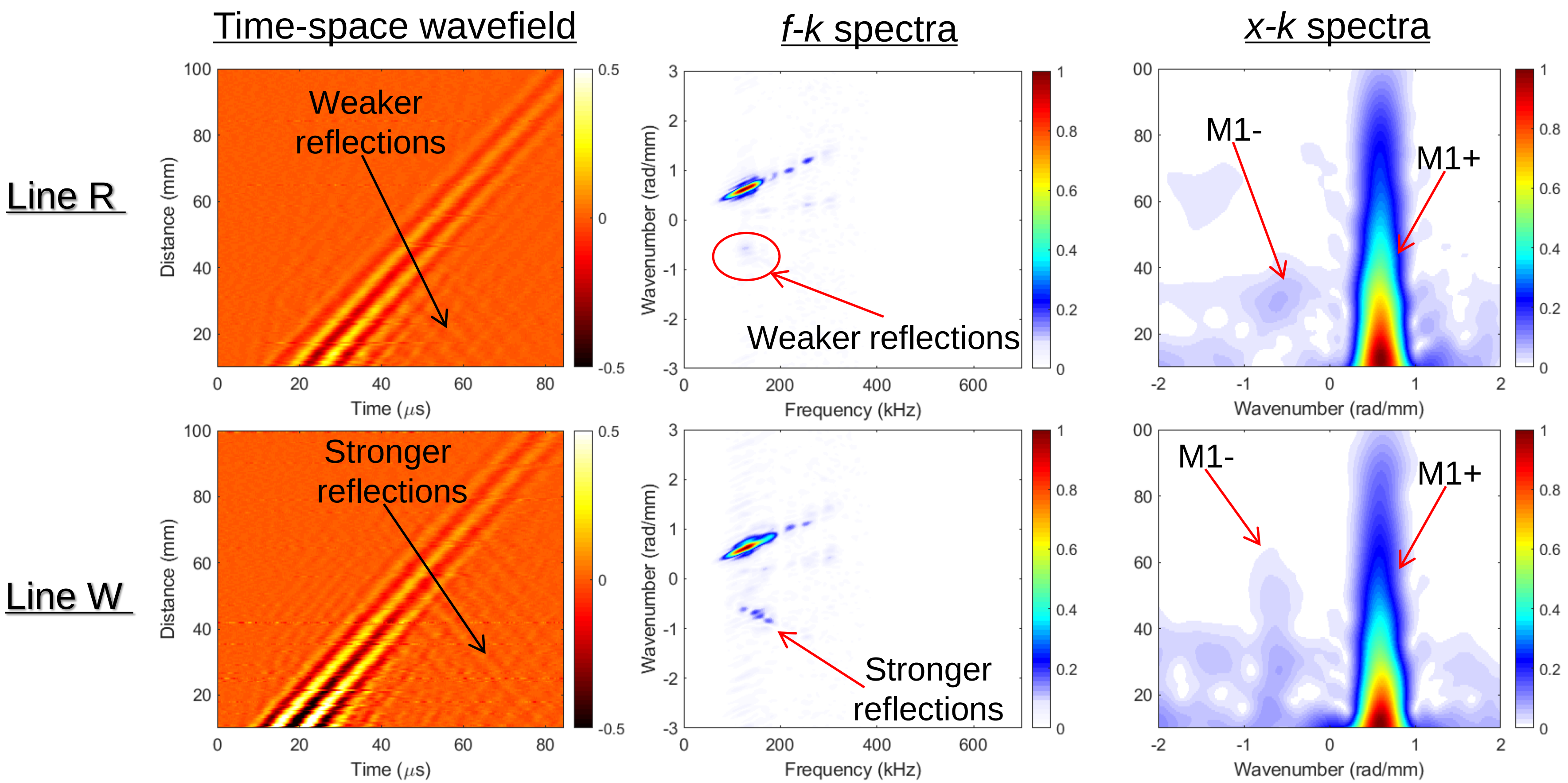


Dispersion curves



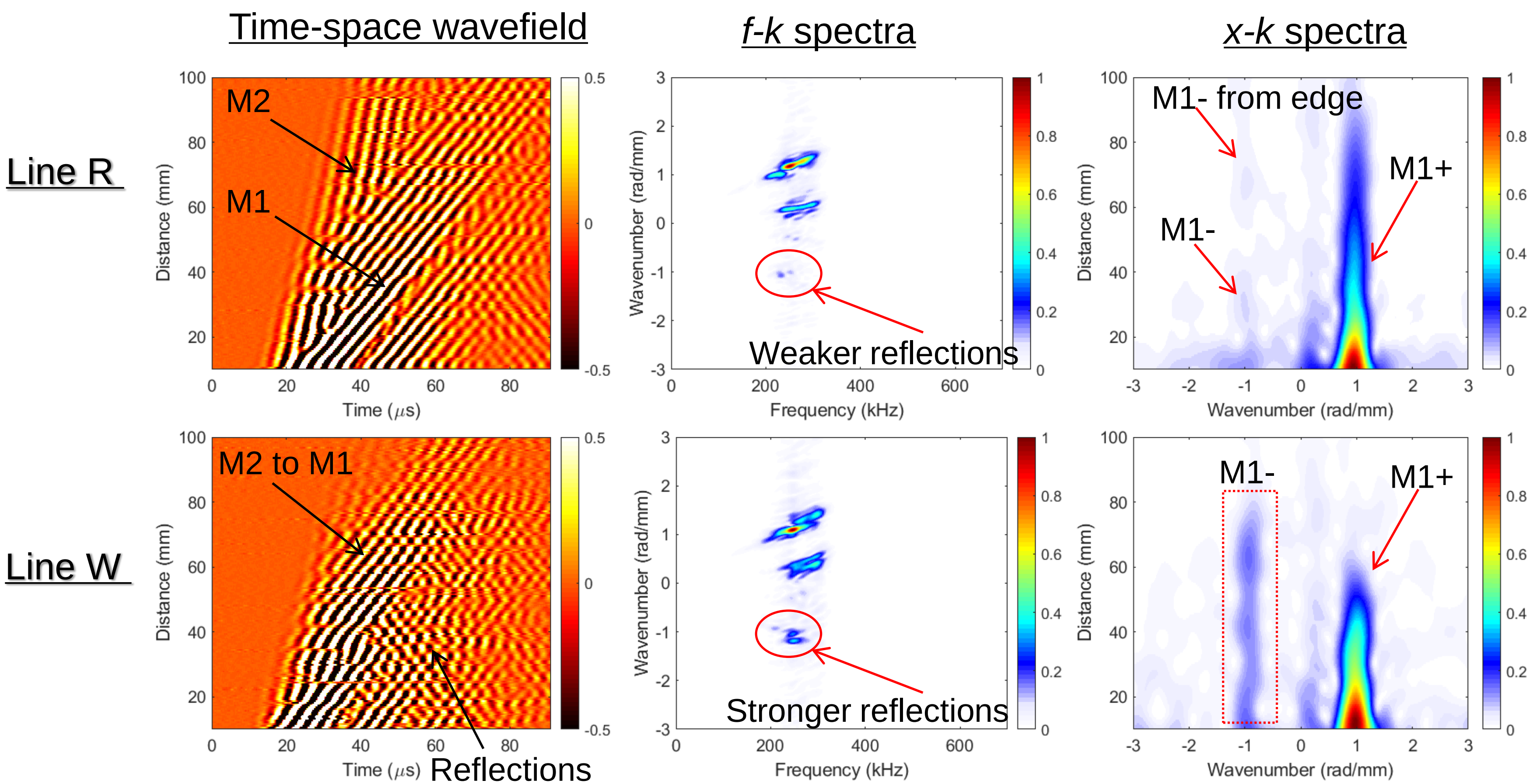
1D inspection results – 120 kHz

- Stronger reflections along line W.
- Longer distance of negative M1 mode appear indicating longer wrinkle range along line W than line R.



1D inspection results – 210 kHz

- Two Lamb waves excited
- Stronger wave interaction observed



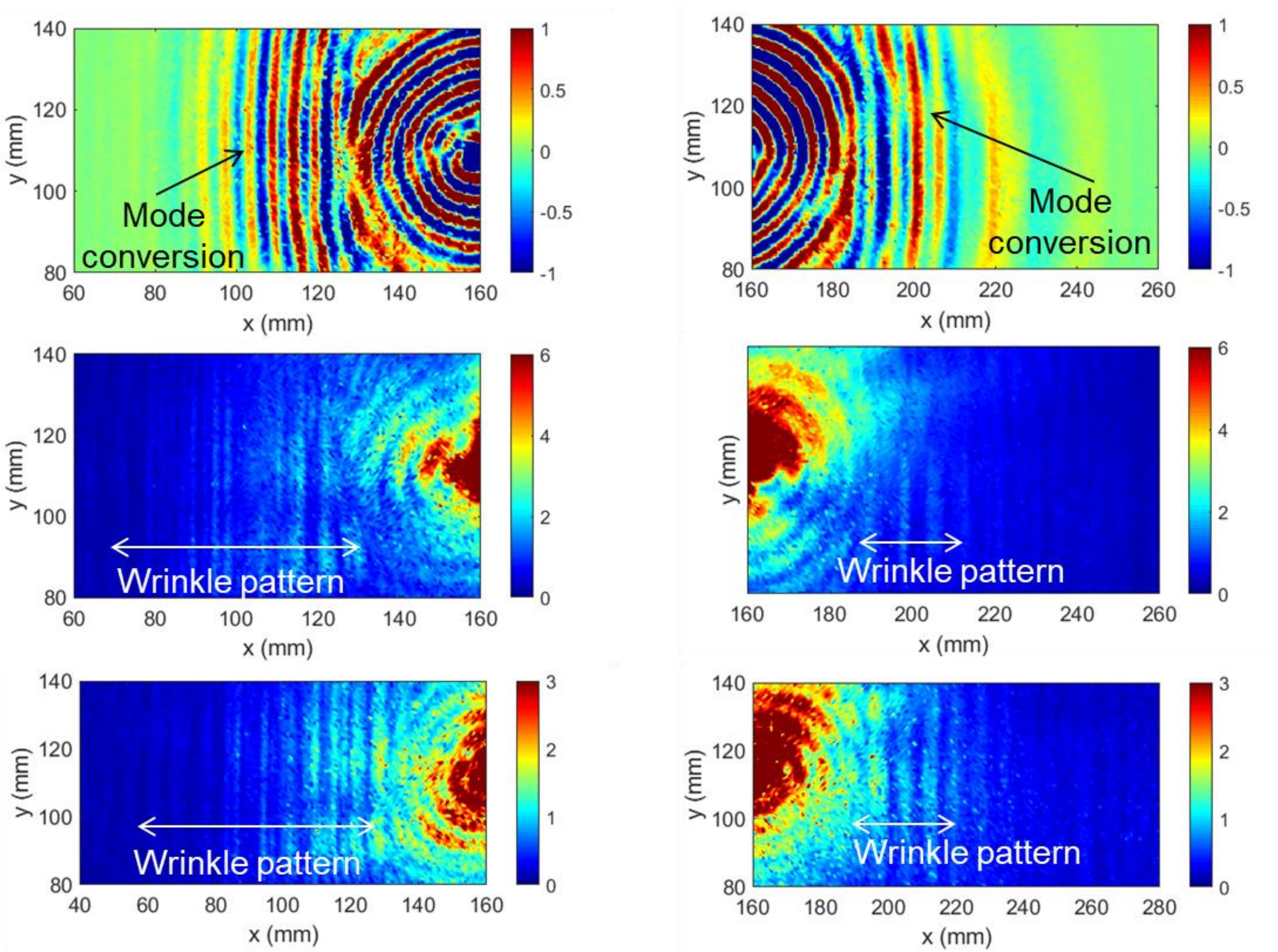
2D inspection results at 210 kHz

Wrinkle region | Reference region

Wavefield on side 1

Wavefield imaging on side 1

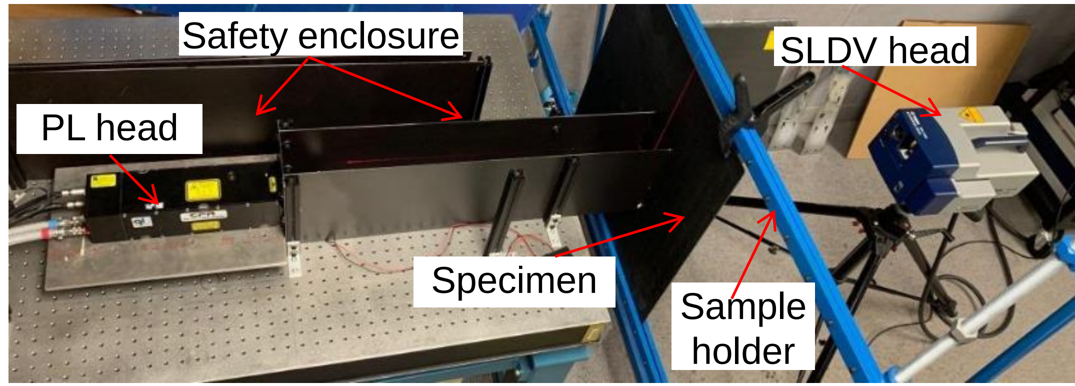
Wavefield imaging on side 2



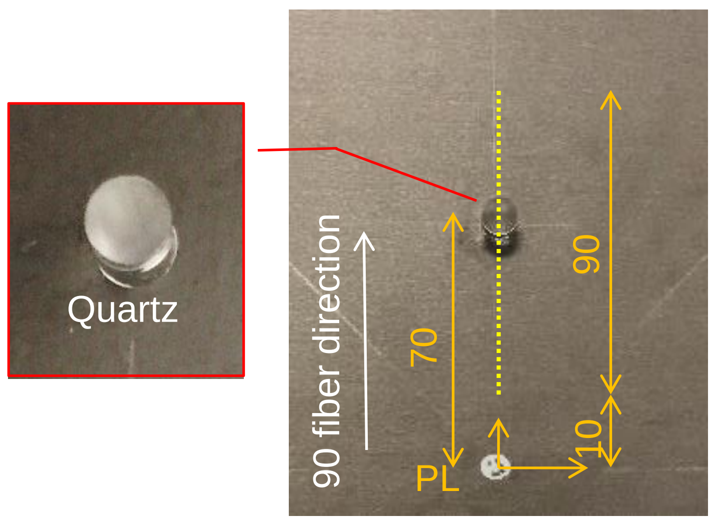
Subtask 4.2: inspection with non-contact PL-SLDV system

- Specimen
  - 8-ply CFRP with layup $[0,45,90,-45]_s$
  - Defect at y=70 mm
- Actuation: 100 mJ with aluminum foil enhancement
- Sensing: Along 90 fiber direction with 1 mm spatial resolution

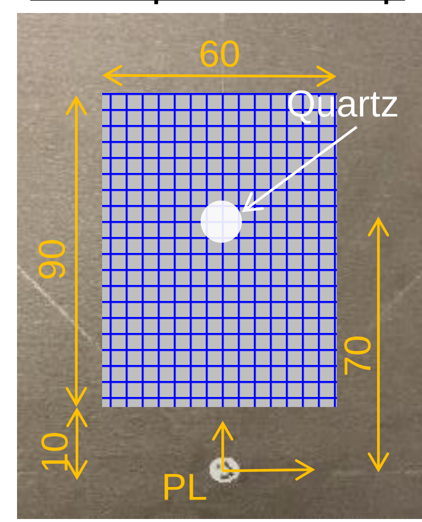
Experimental setup



1D inspection setup



2D inspection setup

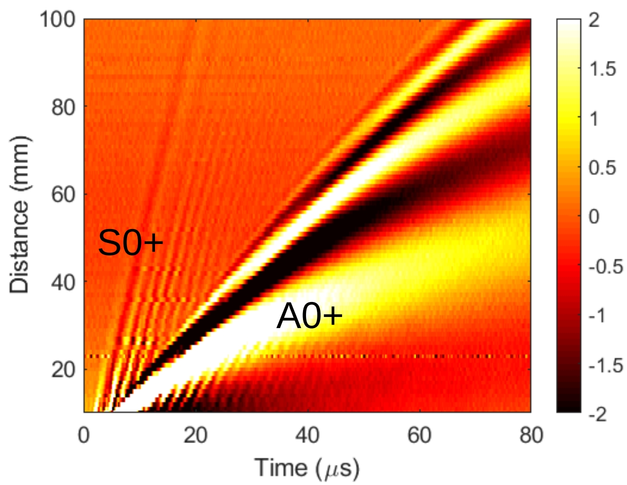


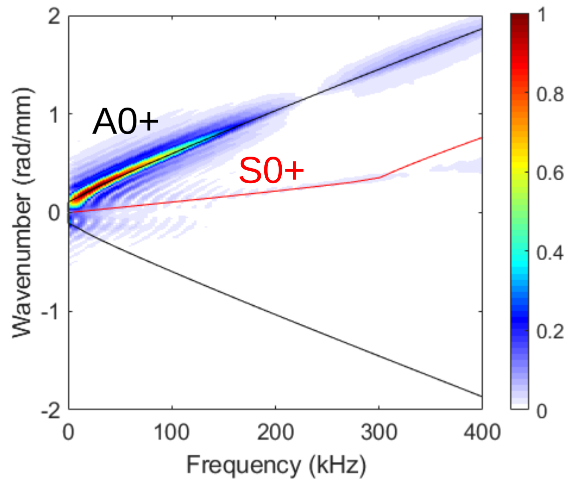
1D inspection results

Time-space wavefield

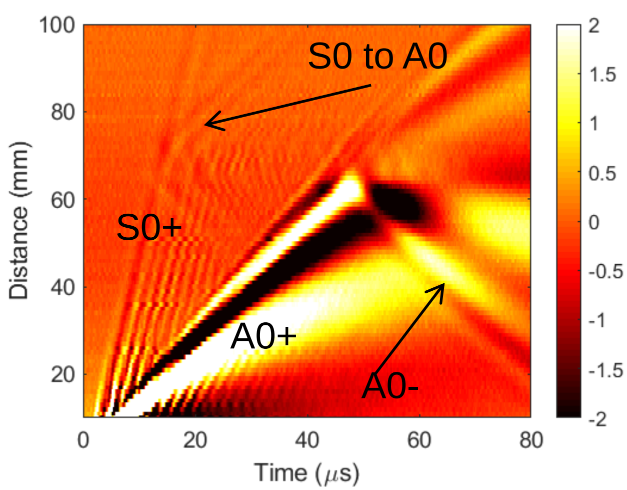
f-k spectra

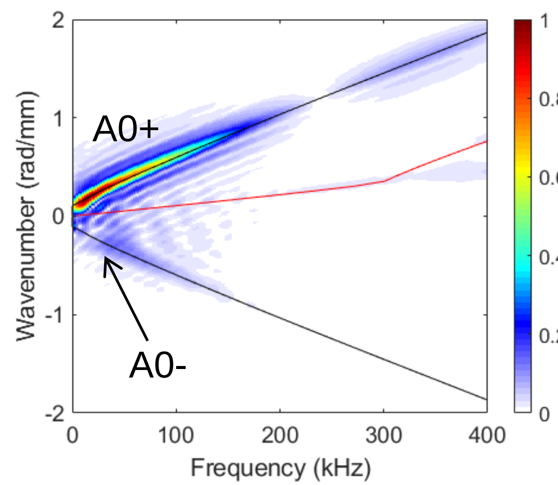
Pristine



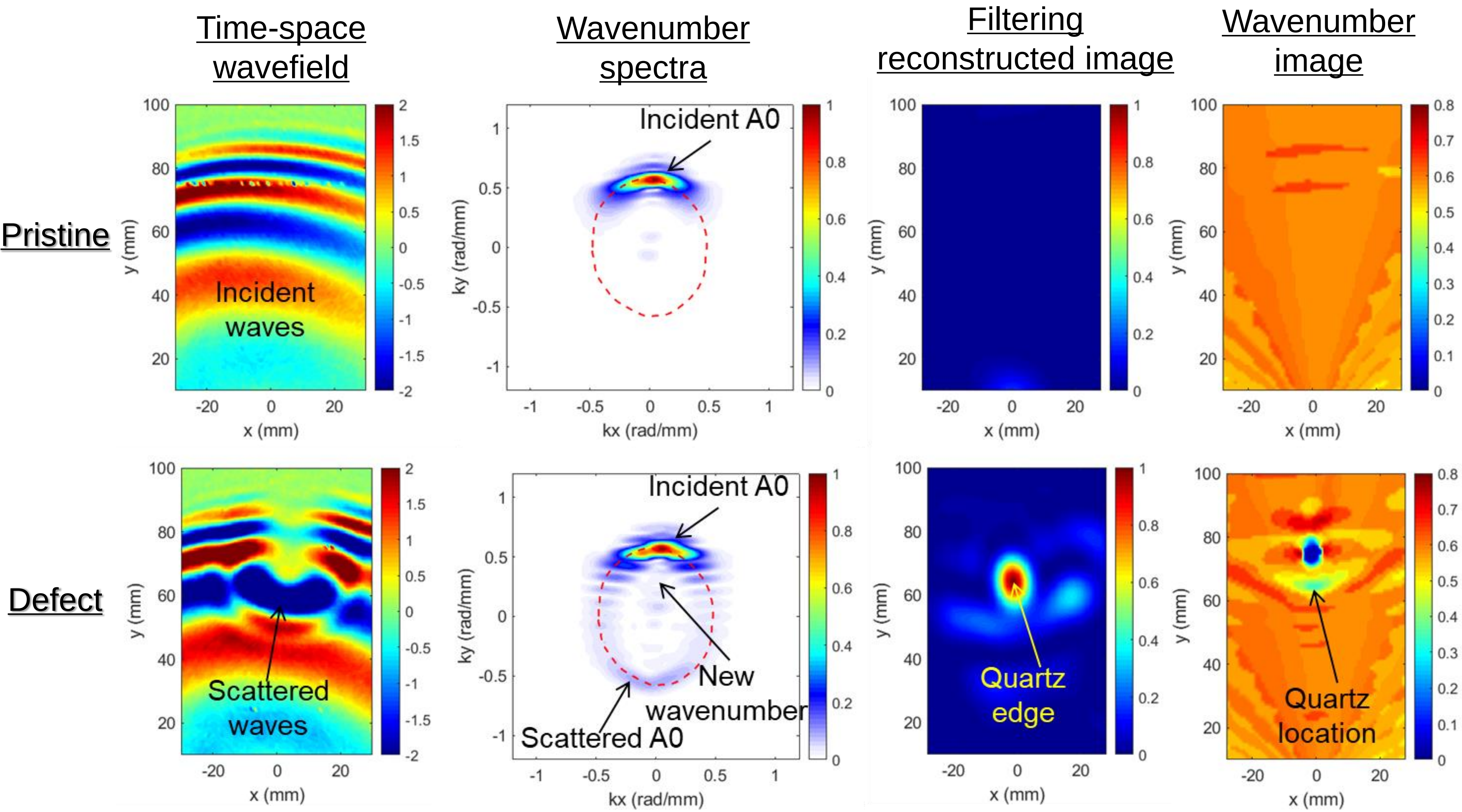


Defect





2D inspection results



Progress of Task 4

25% of Task 4 has been completed

- Case studies in composite structures
  - Wrinkle detection
- PL-SLDV system evaluation on CFRP plates

Future work

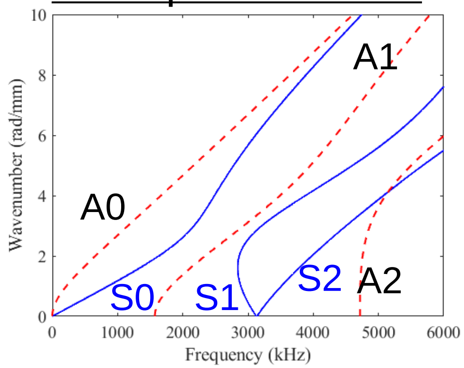
- More case studies on CFRP plates
  - Porosity
  - Delamination
- Robotic PL-SLDV system
- Complex defect detection with network-PZT-SLDV system

Summaries and conclusions

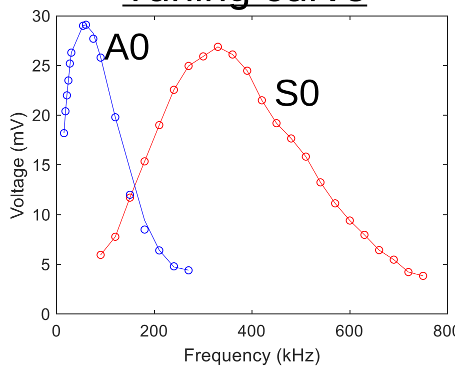
70% of the proposed tasks has been completed

Task 1: Fundamental study

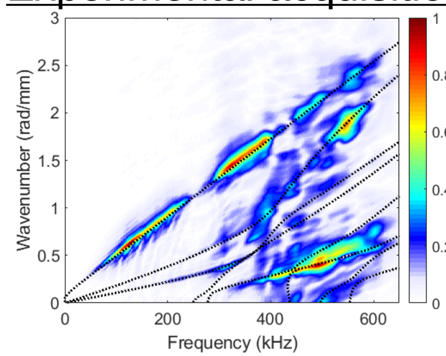
f-k dispersion curve



Tuning curve

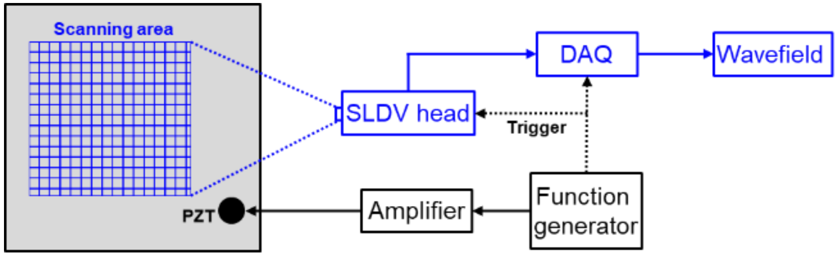


Experimental acquisition



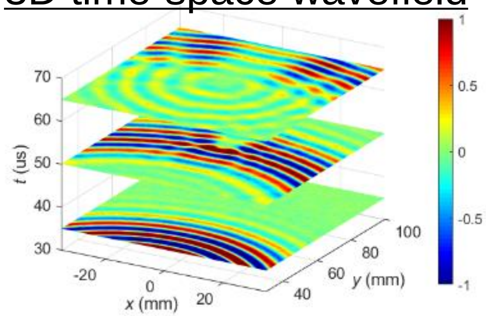
Task 2: Lamb wave based NDE methodology

PZT-SLDV system

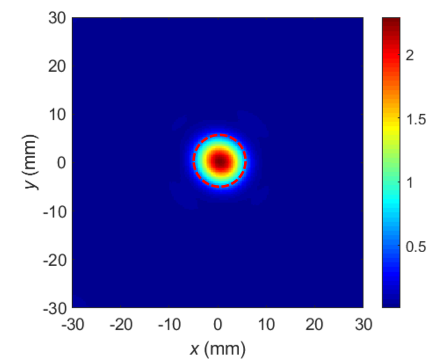


(Ma and Yu, 2019)

3D time-space wavefield



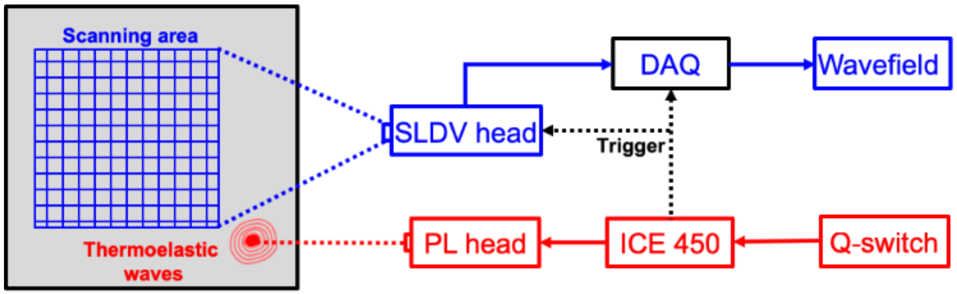
Synthetic imaging



Summaries and conclusions

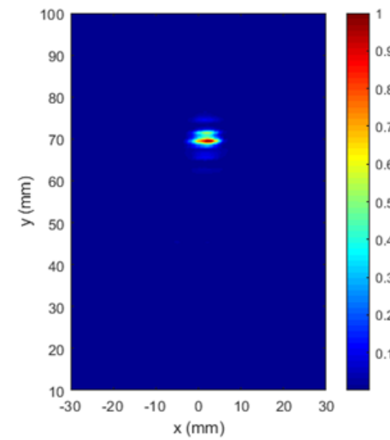
Task 3: Non-contact PL-SLDV system

PL-SLDV system



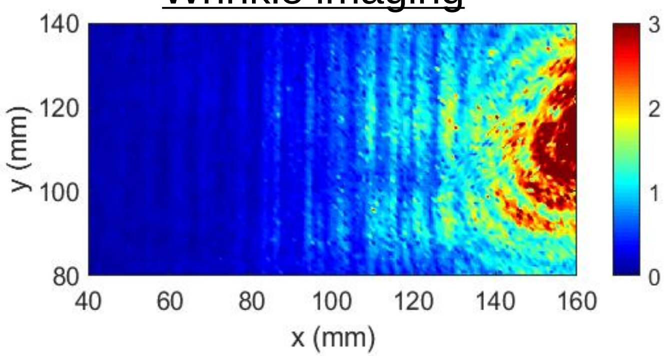
(Ma and Yu, 2019)

Crack imaging

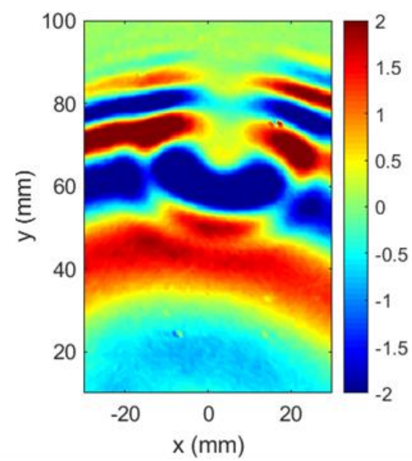


Task 4: Applications

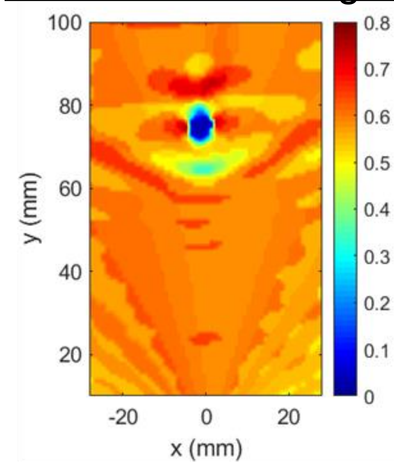
Wrinkle imaging



PL-SLDV measured wavefield



Wavenumber imaging



Timeline

Task	Descriptions	1 year after proposal												Completeness (%)	
		1	2	3	4	5	6	7	8	9	10	11	12		
Task 1	Analytical study of Lamb wave													100%	60%
	Experimental study of Lamb wave													80%	
	Analytical study of PL excited Lamb waves													0%	
Task 2	Partial non-contact PZT-SLDV NDE system overview													100%	100%
	Lamb wave acquisition and characterization													100%	
	Lamb wavefield imaging methodology													100%	
	Multiactuator wavefield imaging methodology													100%	
Task 3	PL-SLDV Lamb wave NDE system calibration													100%	100%
	Pulsed laser Lamb wave excitation on metallic structures													100%	
Task 4	Non-contact evaluation in composite structures													75%	25%
	Case studies and guideline development for Lamb wave NDE in composite structures													25%	
	Network-PZT-SLDV NDE in plate-like structures with complex discontinuities/defects													0%	
Dissertation														0%	0%

Expected contributions

- Quantitative ultrasonic Lamb wave NDE methods that do not require prior knowledge of the material properties through experimental acquisition of dispersion curves
- A high-resolution synthetic imaging method using a network-PZT-SLDV system with demonstrated capabilities of imaging discontinuities with complex profiles
- Fully non-contact ultrasonic NDE and accompanied evaluation methods through PL-SLDV system
- Lamb wave NDE case studies and guidelines for rapid inspection in composites with typical but less reported defects such as wrinkles and porosity, in addition to delamination

Publications

1 Journal Article

- Tian, Z.; Howden, S.; **Ma, Z.**; Xiao, W.; and Yu, L. (2019) "Pulsed laser-scanning laser Doppler vibrometer (PL-SLDV) phased arrays for damage detection in aluminum plates," Mechanical Systems and Signal Processing, Vol. 121, pp.158-170, 2019.

1 Conference Paper

- **Ma, Z.**; and Yu, L. (2019 April) "Lamb wave defect detection and evaluation using a fully non-contact laser system," In Health Monitoring of Structural and Biological Systems XIII, Vol. 10972, p. 1097221, International Society for Optics and Photonics.

1 US patent under review

- Yu, L.; **Ma, Z.**; Tian, Z.; and Xiao, W. (2019) "Network wavefield imaging methods for quantification of complex discontinuity in plate-like structures," US Patent Application, No.: 16/432,159

1 Poster Presentation

- **Ma, Z.**; and Yu, L. "Lamb wave based nondestructive evaluation on metallic plates," Poster session presented at SC State Conference, 2019 April 8, Greenville, SC.

Acknowledgements

- Academic advisor: Dr. Lingyu Yu
- My committee
  - Dr. Victor Giurgiutiu
  - Dr. Yuh Chao
  - Dr. Paul Ziehl
- VSHM colleagues
- My family and friends
- Financial supports
  - University of south Carolina
  - DoE Integrated Research Program
  - NASA*

*Parts of the proposal are based upon work supported by National Aeronautics and Space Administration (NASA) under Award Nos. NNL09AA00A and 80LARC17C0004. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the NASA.

Thank you!