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Lamb Wave Nondestructive Evaluation and Imaging on Plate-like Structures

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PhD Dissertation Defense

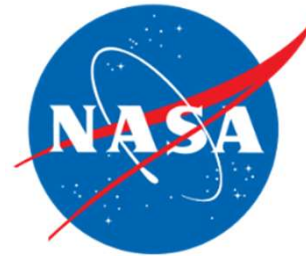
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Outline

- ❑ Research background and objectives
- ❑ State of the art
- ❑ Part I: Lamb wave based nondestructive evaluation/structural health monitoring (NDE/SHM) systems and methodologies
 - Lamb wave fundamental study
 - Lamb wave wavefield analysis methods
 - Development of a noncontact/remote laser system
- ❑ Part II: Various NDE/SHM applications
 - Applications on aerospace structures
 - Applications on nuclear structures
- ❑ Conclusions, major contributions, and future work

Research background and motivation

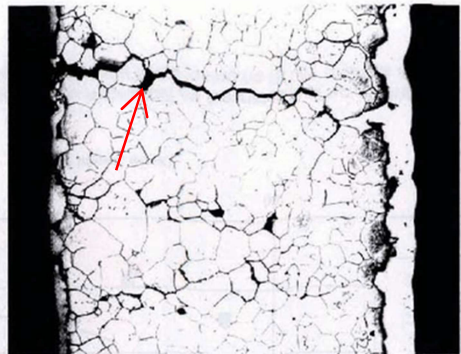
- ❑ Structure components are designed with a certain service life. Damage may occur due to aging or any unexpected events, which may result in structural failure.
- ❑ NDE methods are means that diagnose the structural health in a noninvasive manner. In situ NDE, also known as SHM, normally integrated with the structure, performs online NDE and monitors the target structure in a periodical manner.
- ❑ Effective NDE and/or SHM are critical through their service life to ensure structural components and systems perform their function in a reliable and cost-effective fashion.

Bird strike impact damage



<https://www.osti.gov/servlets/purl/1115103>

Stress corrosion cracking in a steel tube



(Cattant et al., 2008)

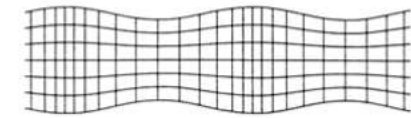
Robotic inspection on a fuselage



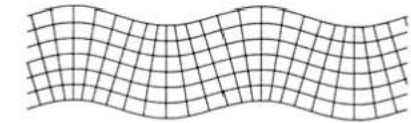
<https://metrology.news/robotic-inspection-to-allow-safer-more-cost-effective-aircraft-manufacturing-processes/>

Lamb wave based NDE/SHM

- ❑ Lamb waves are specific type of guided waves that propagate in plate-like structures
- ❑ Advantages
 - Lamb waves can propagate long distance
 - Lamb waves are sensitive to various defect and damage types
 - Many damage detection results are promising



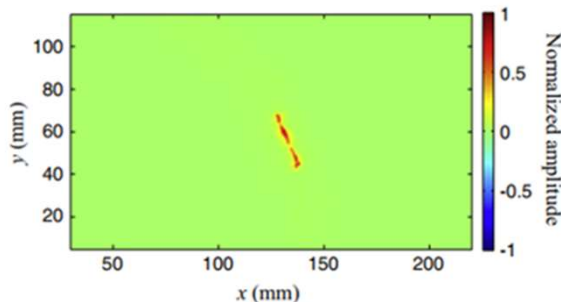
Symmetric Lamb Wave



Anti-Symmetric Lamb Wave

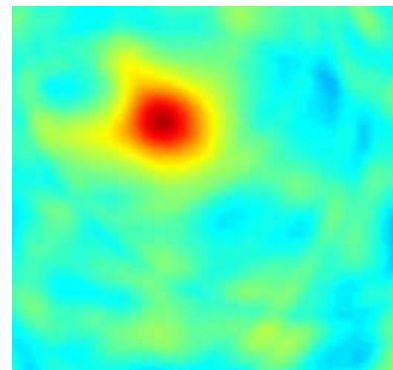
(Roy et al., 2014)

Crack detection



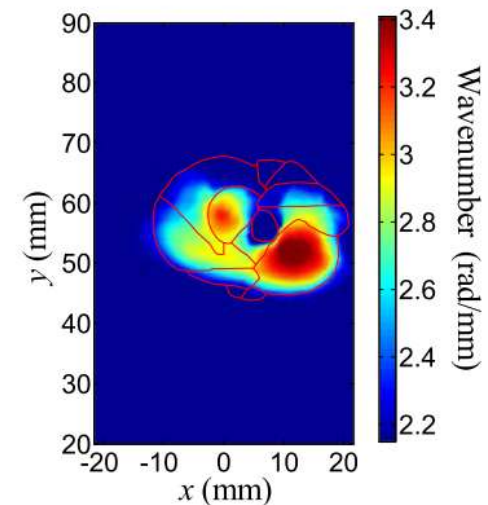
(Yu et al., 2013)

Material loss detection



(Michaels, 2008)

Impact damage detection

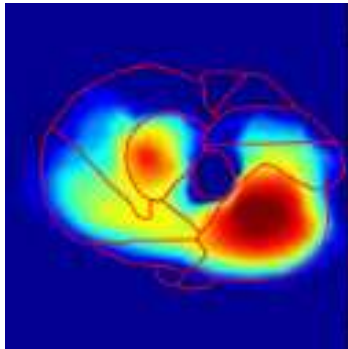


(Tian et al., 2015)

Lamb wave NDE/SHM challenges

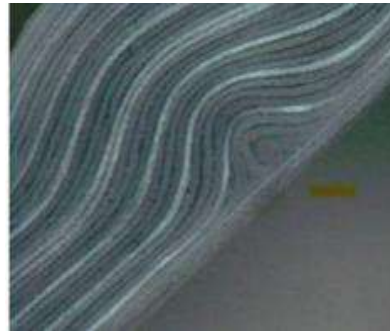
- ❑ Complex damage is difficult to quantify with its full profile including their sizes and shapes
- ❑ Current excitation and sensing systems need to be improved towards more flexible applications
- ❑ The reliability and effectiveness of the Lamb wave based systems and methodologies in real world applications are still need to be investigated and evaluated

Impact damage evaluation



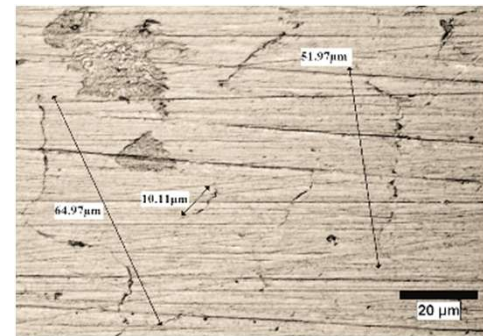
(Tian et al., 2015)

Out-of-plane wrinkles in composite structure



(Hallander et al., 2013)

Stress corrosion cracking in a carbon steel structure



(Zeitvogel et al., 2014)

Research work

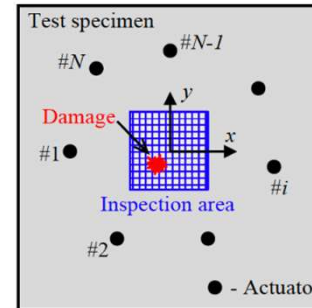
Part I: Lamb wave NDE/SHM system and methodology development

- ❑ Lamb wave based actuator network imaging system and method that can quantify damages with complex profiles
- ❑ A reliable noncontact/remote NDE system combined with effective imaging methods

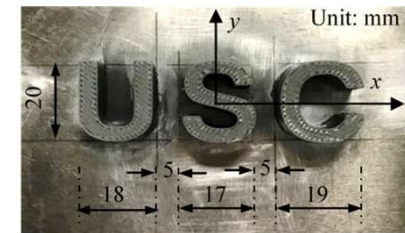
Part II: Various NDE/SHM applications to prove the system and methodology reliability

- ❑ Complex damage profile quantification with great details
- ❑ Crack quantification with the developed noncontact NDE systems
- ❑ Various typical composite defects evaluation with effective NDE system setup and imaging algorithms
- ❑ Typical nuclear structure damage evaluation such as SCC quantification and material thickness identification with reasonable accuracy

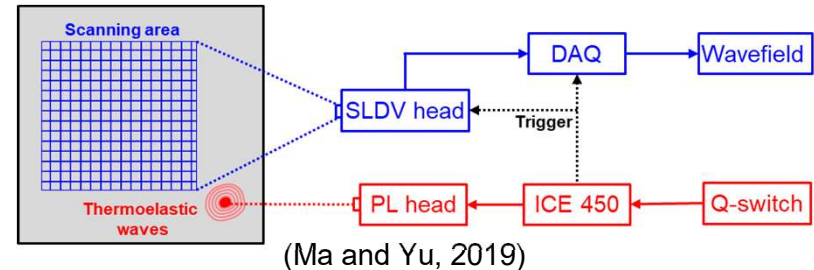
Actuator network system



A complex letter cluster damage



Non-contact PL-SLDV system



Wrinkle defect in composites



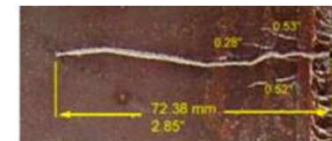
(Courtesy of NASA Langley Research Center and Boeing)

Curved composite plate



(Courtesy of NASA Langley Research Center and ACP members)

SCC in welded steel plate



State of the art

❑ Transducers for Lamb wave actuation and sensing

Contact type

Ultrasonic probes



<https://www.bakerhughesds.com/waygate-technologies/ultrasonic-probes-transducers/immersion-probes>

Optical fibers



<https://www.fiberguide.com>

PZT transducer



- Compact
- Light
- Actuation and sensing

Noncontact type

Pulsed laser



<https://www.quantel-laser.com>

SLDV system



<https://www.polytec.com>

Electromagnetic acoustic Transducers (EMAT)



<https://www.olympus-ims.com>

Air-coupled transducers (ACT)



<http://www.starmans.net/product/air-coupled/>

➤ Pulsed laser

- Based on thermal-elastic effect
- Generate high energy wide band Lamb waves in a noncontact and remote manner

➤ SLDV system

- Based on the Doppler effect
- Measure multi-dimensional wavefield data with high spatial resolution

State of the art

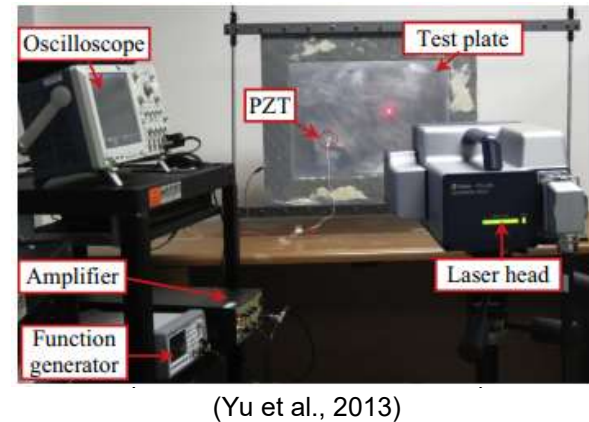
□ Lamb wave wavefield actuation and sensing strategies

**Partial
noncontact
system**

PZT-SLDV system

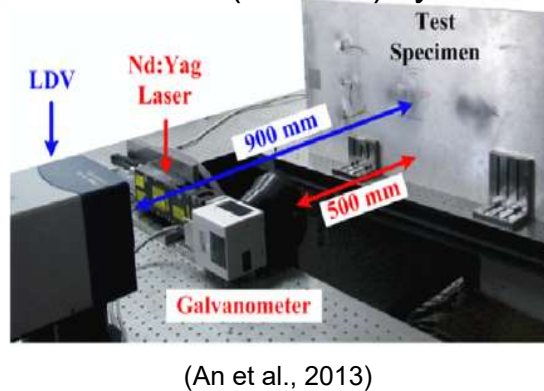


PZT-SLDV system

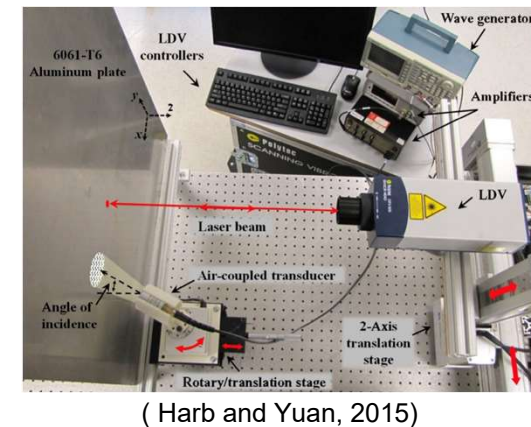


Pulsed laser-laser Doppler vibrometer (PL-LDV) system

**Fully
Noncontact
system**



ACT-LDV system

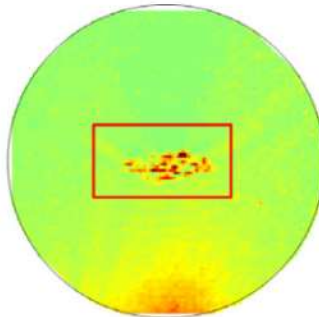


State of the art

□ Lamb wave based NDE/SHM imaging algorithms

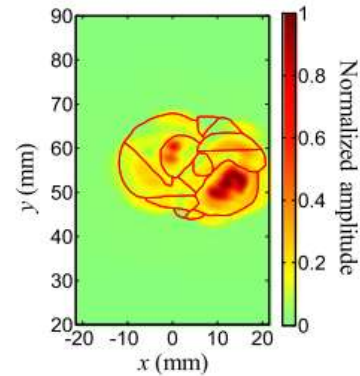
**Single actuator
employed**

Filtering imaging



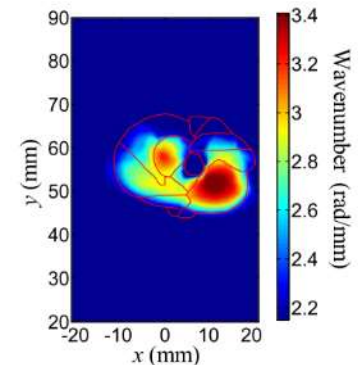
(Sohn et al., 2011)

Filtering reconstruction imaging



(Tian et al., 2015)

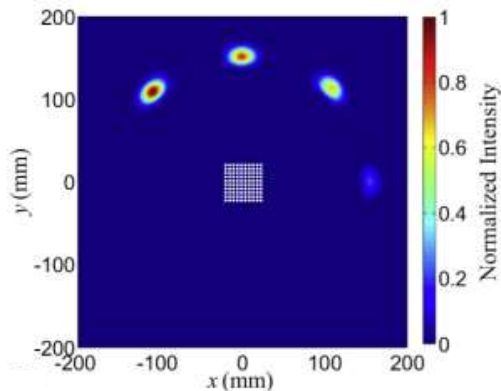
Wavenumber imaging



(Tian et al., 2015)

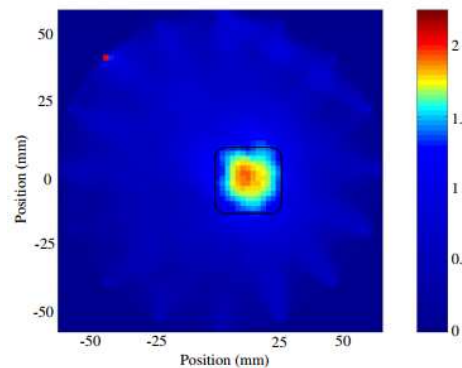
**Multiactuator
employed**

Phased array imaging



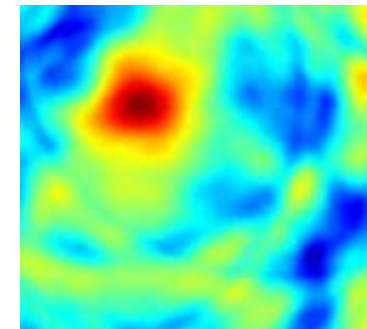
(Tian et al., 2019)

Tomography imaging



(An et al., 2013)

Sparse array imaging



(Michaels, 2008)

Part I: Lamb wave NDE/SHM system and
methodology development
Lamb wave fundamental study

Lamb waves in two-layer structures

One-layer isotropic plate

- ❑ Lamb wave are dispersive and multi-modal
- ❑ General solutions of Rayleigh-Lamb wave equations:

$$u_x = e^{i(\xi x - \omega t)} (i\xi \sin \eta_P y A_1 + i\xi \cos \eta_P y A_2 + i\eta_S \cos \eta_S y B_1 - i\eta_S \sin \eta_S y B_2)$$

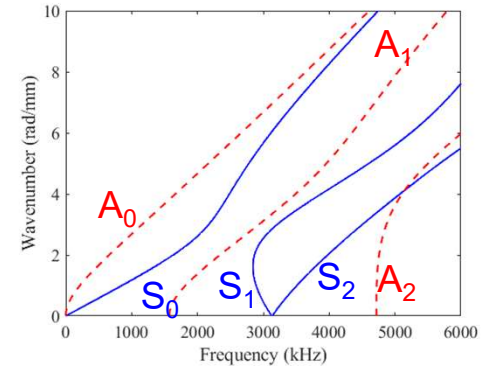
$$u_y = e^{i(\xi x - \omega t)} (\eta_P \cos \eta_P y A_1 - \eta_P \sin \eta_P y A_2 + \xi \sin \eta_S y B_1 + \xi \cos \eta_S y B_2)$$

$$\sigma_{xy} = e^{i(\xi x - \omega t)} [2i\mu\xi\eta_P \cos \eta_P y A_1 - 2i\mu\xi\eta_P \sin \eta_P y A_2 + i\mu(\xi^2 - \eta_S^2) \sin \eta_S y B_1 + i\mu(\xi^2 - \eta_S^2) \cos \eta_S y B_2]$$

$$\sigma_{yy} = e^{i(\xi x - \omega t)} [\mu(\xi^2 - \eta_S^2) \sin \eta_P y A_1 + \mu(\xi^2 - \eta_S^2) \cos \eta_P y A_2 + 2\mu\xi\eta_S \cos \eta_S y B_1 - 2\mu\xi\eta_S \sin \eta_S y B_2]$$

(Giurgiutiu, 2008)

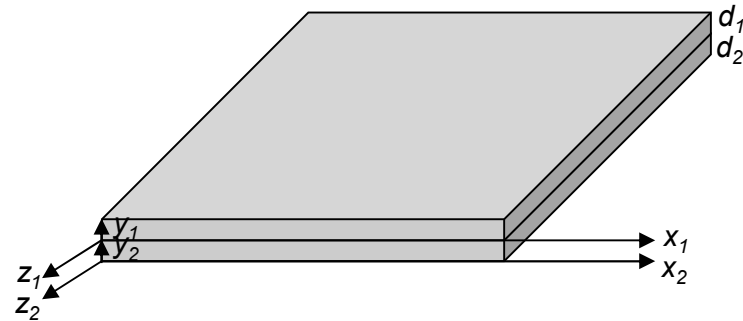
Dispersion curves on a 1-mm (one layer) aluminum plate



Two-layer structure (each layer is isotropic with different materials)

- ❑ Model assumption:
 - The two layers are perfectly bonded together
 - Straight crest waves propagating along x direction
 - z-invariant problem
- ❑ Boundary conditions:
 - At top and bottom surface of each layer: stress free
 - At the interface: the displacement and stress are continuous
- ❑ Analytical method: Global matrix method

Two-layer plate



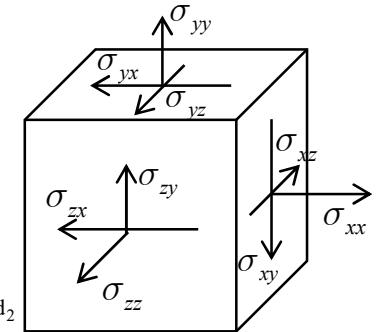
Boundary conditions

$$\sigma_{xy}^1 |_{y_1=d_1} = 0, \sigma_{yy}^1 |_{y_1=d_1} = 0$$

$$\sigma_{xy}^2 |_{y_2=0} = 0, \sigma_{yy}^2 |_{y_2=0} = 0$$

$$u_x^1 |_{y_1=0} = u_x^2 |_{y_2=d_2}, u_y^1 |_{y_1=0} = u_y^2 |_{y_2=d_2}$$

$$\sigma_{xy}^1 |_{y_1=0} = \sigma_{xy}^2 |_{y_2=d_2}, \sigma_{yy}^1 |_{y_1=0} = \sigma_{yy}^2 |_{y_2=d_2}$$



Characteristic equation and solutions

□ General solutions for each layer

$$u_x = e^{i(\xi x - \omega t)} (i\xi \sin \eta_p y A_1 + i\xi \cos \eta_p y A_2 + i\eta_s \cos \eta_s y B_1 - i\eta_s \sin \eta_s y B_2)$$

$$u_y = e^{i(\xi x - \omega t)} (\eta_p \cos \eta_p y A_1 - \eta_p \sin \eta_p y A_2 + \xi \sin \eta_s y B_1 + \xi \cos \eta_s y B_2)$$

$$\sigma_{xy} = e^{i(\xi x - \omega t)} [2i\mu\xi\eta_p \cos \eta_p y A_1 - 2i\mu\xi\eta_p \sin \eta_p y A_2 + i\mu(\xi^2 - \eta_s^2) \sin \eta_s y B_1 + i\mu(\xi^2 - \eta_s^2) \cos \eta_s y B_2]$$

$$\sigma_{yy} = e^{i(\xi x - \omega t)} [\mu(\xi^2 - \eta_s^2) \sin \eta_p y A_1 + \mu(\xi^2 - \eta_s^2) \cos \eta_p y A_2 + 2\mu\xi\eta_s \cos \eta_s y B_1 - 2\mu\xi\eta_s \sin \eta_s y B_2]$$

□ Boundary conditions

$$\sigma_{xy}^1|_{y_1=d_1} = 0, \sigma_{yy}^1|_{y_1=d_1} = 0$$

$$\Longrightarrow \sigma_{xy}^2|_{y_2=0} = 0, \sigma_{yy}^2|_{y_2=0} = 0$$

$$u_x^1|_{y_1=0} = u_x^2|_{y_2=d_2}, u_y^1|_{y_1=0} = u_y^2|_{y_2=d_2}$$

$$\sigma_{xy}^1|_{y_1=0} = \sigma_{xy}^2|_{y_2=d_2}, \sigma_{yy}^1|_{y_1=0} = \sigma_{yy}^2|_{y_2=d_2}$$

□ Characteristic equation

$$\Longrightarrow \mathbf{D}(\xi, \omega) \begin{bmatrix} A_1^1, A_2^1, B_1^1, B_2^1, A_1^2, A_2^2, B_1^2, B_2^2 \end{bmatrix}^T = 0 \Longrightarrow |\mathbf{D}(\xi, \omega)| = 0 \Longrightarrow$$

□ Solutions

$$\Longrightarrow \square \text{ Frequency wavenumber pairs } \xi, \omega \Longrightarrow \square \text{ Phase velocity } c_p = \frac{\omega}{\xi}$$

$$\square \text{ Group velocity } c_g = \frac{d\omega}{d\xi}$$

□ Global matrix $\mathbf{D}(\xi, \omega)$

$$D(\xi, \omega) = \begin{bmatrix} 2\xi\eta_{p1} \cos \eta_{p1} d_1 & -2\xi\eta_{p1} \sin \eta_{p1} d_1 & (\xi^2 - \eta_{s1}^2) \sin \eta_{s1} d_1 & (\xi^2 - \eta_{s1}^2) \cos \eta_{s1} d_1 & 0 & 0 & 0 & 0 \\ (\xi^2 - \eta_{s1}^2) \sin \eta_{p1} d_1 & (\xi^2 - \eta_{s1}^2) \cos \eta_{p1} d_1 & 2\xi\eta_{s1} \cos \eta_{s1} d_1 & -2\xi\eta_{s1} \sin \eta_{s1} d_1 & 0 & 0 & 0 & 0 \\ 2\mu_1\xi\eta_{p1} & 0 & 0 & \mu_1(\xi^2 - \eta_{s1}^2) & -2\mu_2\xi\eta_{p2} \cos \eta_{p2} d_2 & 2\mu_2\xi\eta_{p2} \sin \eta_{p2} d_2 & -\mu_2(\xi^2 - \eta_{s2}^2) \sin \eta_{s2} d_2 & -\mu_2(\xi^2 - \eta_{s2}^2) \cos \eta_{s2} d_2 \\ 0 & \mu_1(\xi^2 - \eta_{s1}^2) & 2\mu_1\xi\eta_{s1} & 0 & -\mu_2(\xi^2 - \eta_{s2}^2) \sin \eta_{p2} d_2 & -\mu_2(\xi^2 - \eta_{s2}^2) \cos \eta_{p2} d_2 & -2\mu_2\xi\eta_{s2} \cos \eta_{s2} d_2 & 2\mu_2\xi\eta_{s2} \sin \eta_{s2} d_2 \\ 0 & \xi & \eta_{s1} & 0 & -\xi \sin \eta_{p2} d_2 & -\xi \cos \eta_{p2} d_2 & -\eta_{s2} \cos \eta_{s2} d_2 & \eta_{s2} \sin \eta_{s2} d_2 \\ \eta_{p1} & 0 & 0 & \xi & -\eta_{p2} \cos \eta_{p2} d_2 & \eta_{p2} \sin \eta_{p2} d_2 & -\xi \sin \eta_{s2} d_2 & -\xi \cos \eta_{s2} d_2 \\ 0 & 0 & 0 & 0 & 2\xi\eta_{p2} & 0 & 0 & \xi^2 - \eta_{s2}^2 \\ 0 & 0 & 0 & 0 & 0 & \xi^2 - \eta_{s2}^2 & 2\xi\eta_{s2} & 0 \end{bmatrix}$$

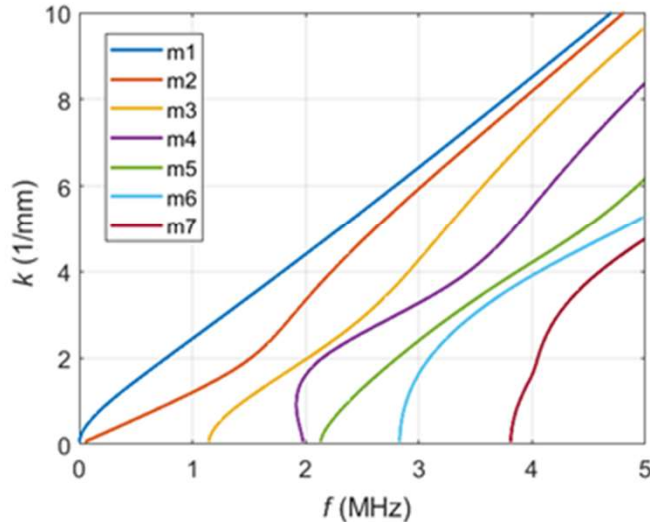
Dispersion curves in a two-layer structure

Material properties of each layer (Nafchi et al., 2012)

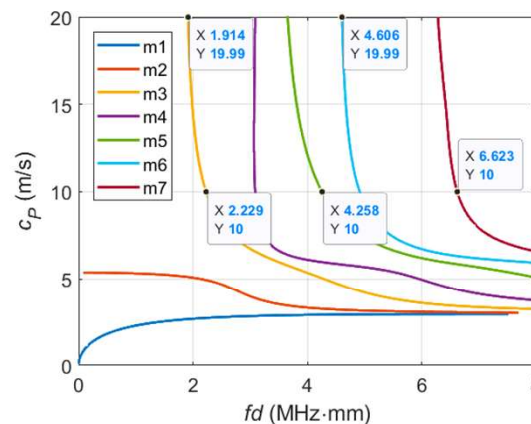
Layer	Material	Thickness (mm)	Pressure wave speed c_P (m/s)	Shear wave speed c_S (m/s)
1	Steel-T304	1.2	5900	3190
2	Aluminum-2024-T3	0.4	6350	3130

Phase velocity dispersion curves

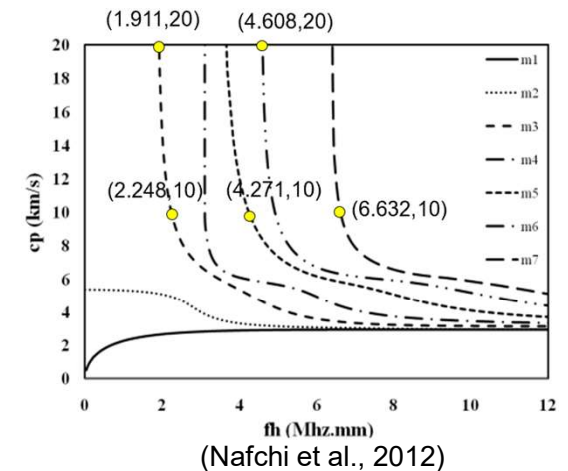
Frequency-wavenumber (f-k) dispersion curves



My calculation



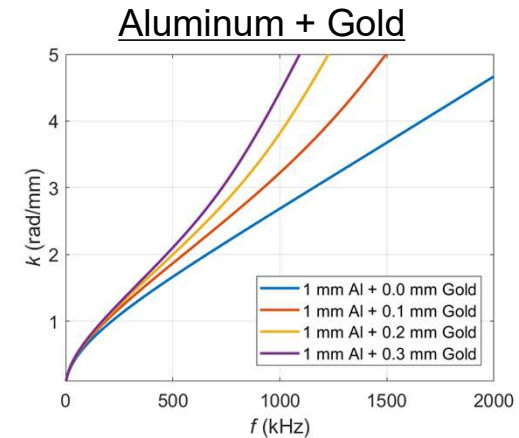
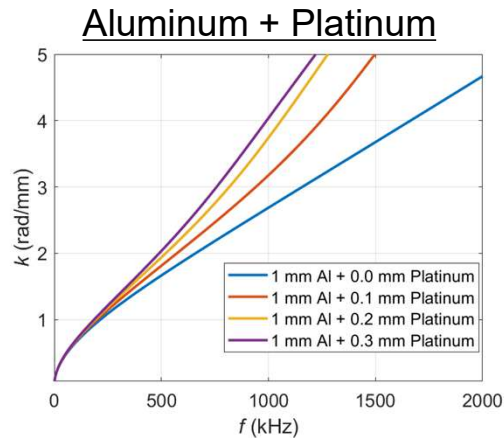
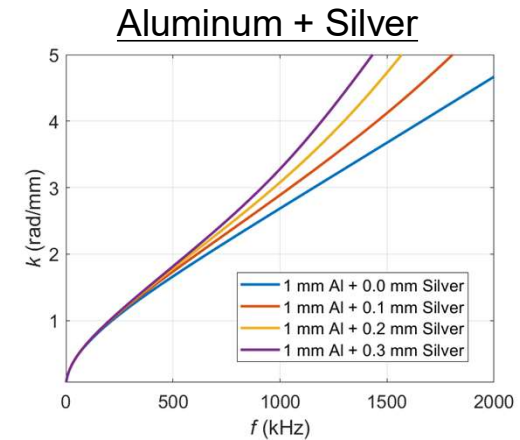
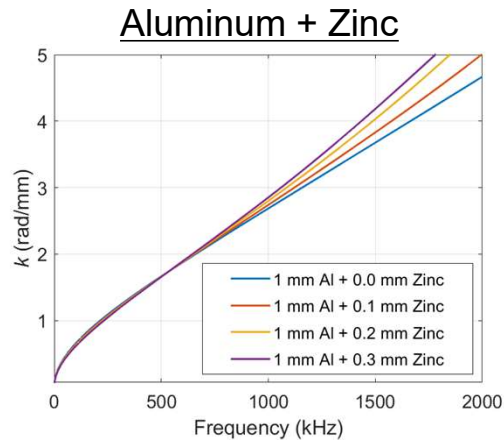
Literature calculation



- ❑ Difference of the selected points:
0.15%, 0.04%, 0.85%, 0.21%, 0.13%
- ❑ The analytical method is verified

Dispersion curve sensitivity study

- ❑ 1 mm aluminum substrate structure with coating layer as: zinc, silver, platinum and gold
- ❑ Layer thickness
 - 0 mm
 - 0.1 mm
 - 0.2 mm
 - 0.3 mm
- ❑ Only the first mode is interested

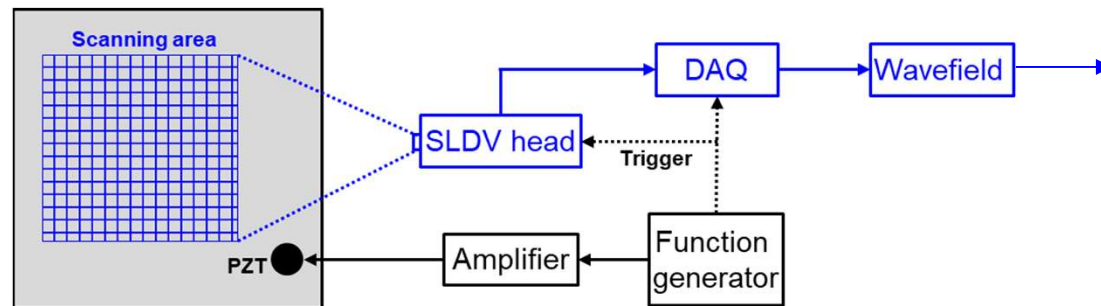


- ❑ Each two-layer structure has its unique dispersion curves
- ❑ The dispersion curves vary with the coating layer thickness for each plate

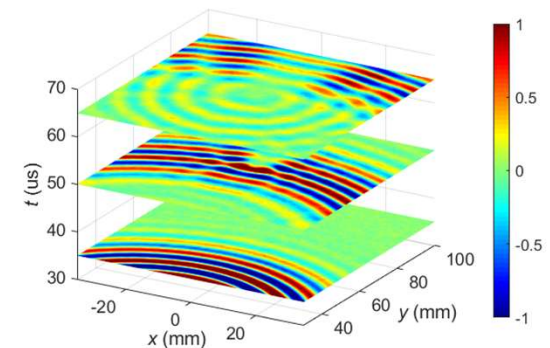
Part I: Lamb wave NDE/SHM system and methodology development

Lamb wave based NDE/SHM methodology

PZT-SLDV system



(Ma and Yu, 2019)

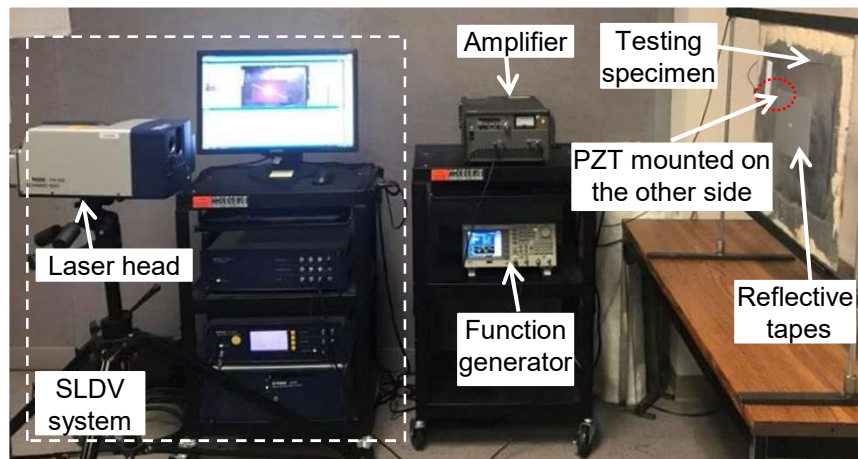


PZT-SLDV Lamb wave SHM/NDE system

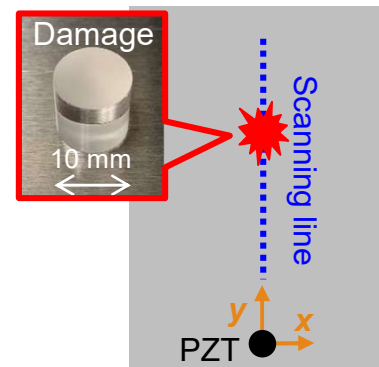
- ❑ Actuation: PZT wafer transducer
- ❑ Wavefield $v(t, \mathbf{x})$ sensing: Polytech PSV-400 SLDV system
 - Measure out-of-plane particle velocity based on Doppler effect
 - Can measure multi-dimensional wavefield data with high spatial resolution
 - The wavefield data contains a wealth of wave characteristics and wave damage interaction signatures

- ❑ Specimen: 1 mm aluminum 2024-T3 plate
- ❑ Actuation: 3-count toneburst at 120 kHz amplified to 50 V_{pp}
- ❑ Sensing: 1 mm spatial resolution

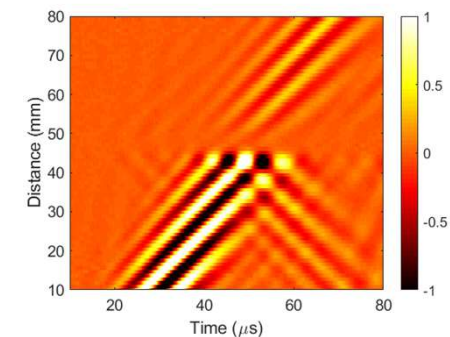
Experimental setup of the PZT-SLDV system



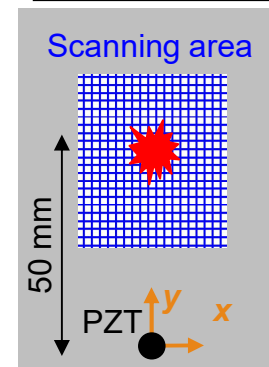
1D line scan



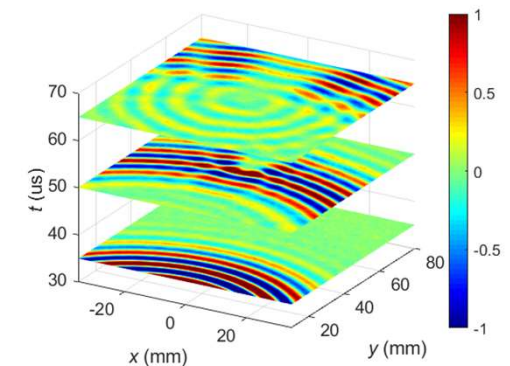
2D wavefield



2D area scan



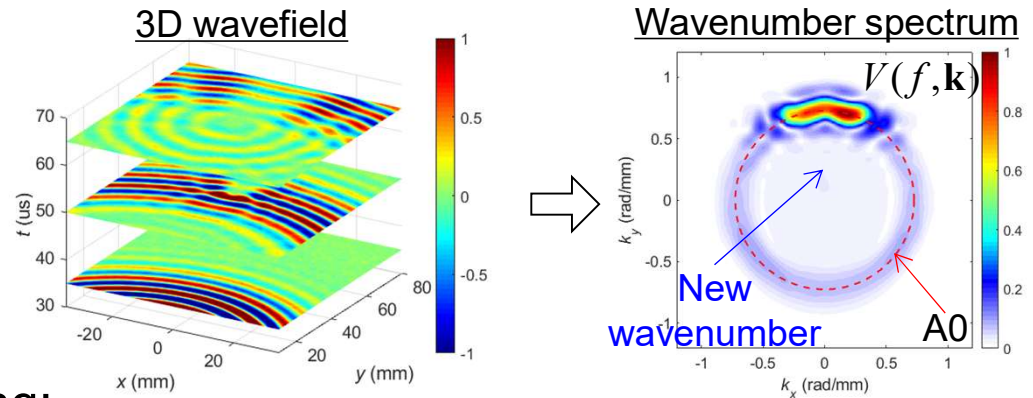
3D wavefield



Filtering reconstruction imaging

- ❑ Multidimensional Fourier analysis:

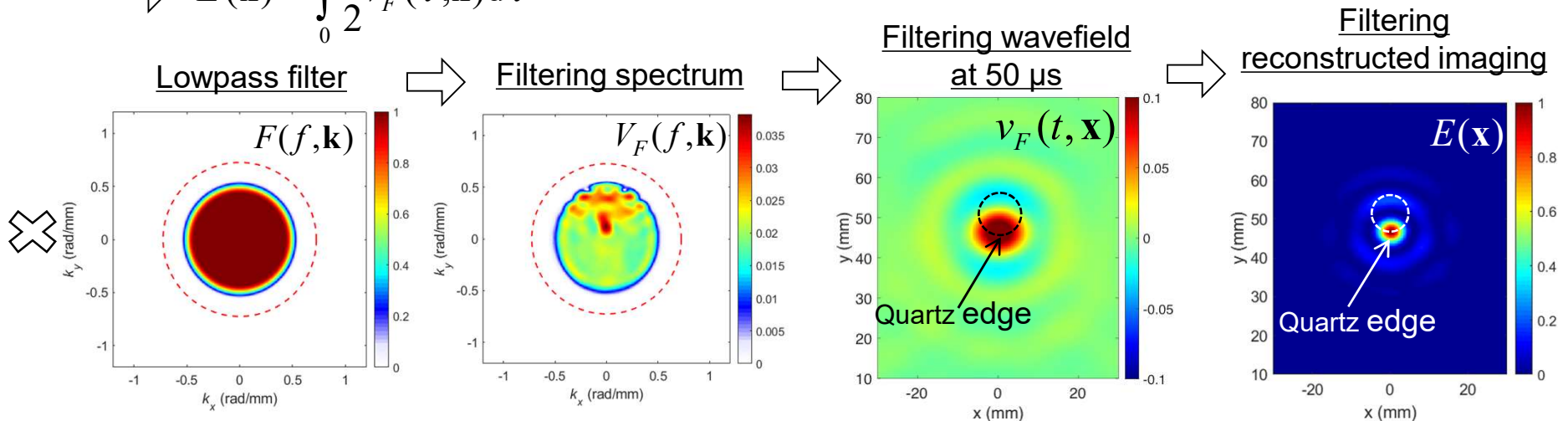
$$V(f, \mathbf{k}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} v(t, \mathbf{x}) e^{-i(2\pi ft - \mathbf{k} \cdot \mathbf{x})} dt d\mathbf{x}$$



- ❑ Filtering reconstruction imaging:

$$V_F(f, \mathbf{k}) = V(f, \mathbf{k}) F(f, \mathbf{k}) \quad \Longrightarrow \quad v_F(t, \mathbf{x}) = \frac{1}{2\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V_F(f, \mathbf{k}) e^{j(2\pi ft - \mathbf{k} \cdot \mathbf{x})} df d\mathbf{k}$$

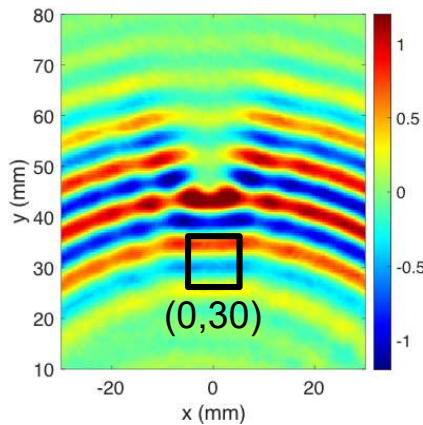
$$\Longrightarrow E(\mathbf{x}) = \int_0^t \frac{1}{2} v_F^2(\tau, \mathbf{x}) d\tau$$



Wavenumber imaging

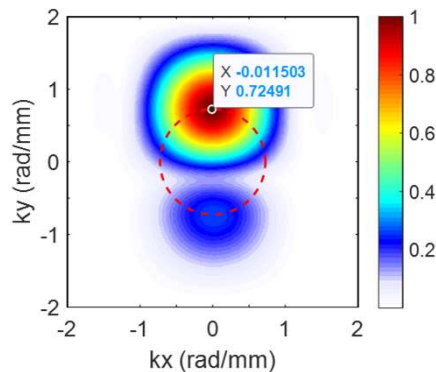
$$S_x(\bar{x}, f, \mathbf{k}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} v(t, \mathbf{x}) W_t(t, \mathbf{x} - \bar{\mathbf{x}}) e^{-i(2\pi ft - \mathbf{k} \cdot \mathbf{x})} dt d\mathbf{x}$$

Wavefield windowing (10 mm by 10 mm)



3D FFT

Wavenumber spectrum (120 kHz)



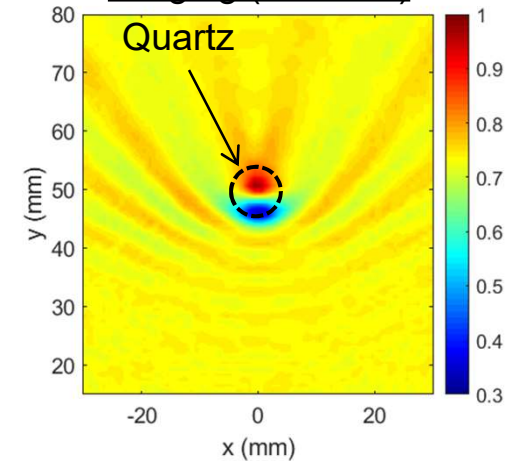
$$\mathbf{k}^*(\bar{\mathbf{x}}, f) = \arg \max_{\mathbf{k}} |S_x(\bar{\mathbf{x}}, f, \mathbf{k})|$$

$$|\mathbf{k}| = \sqrt{k_x^2 + k_y^2}$$

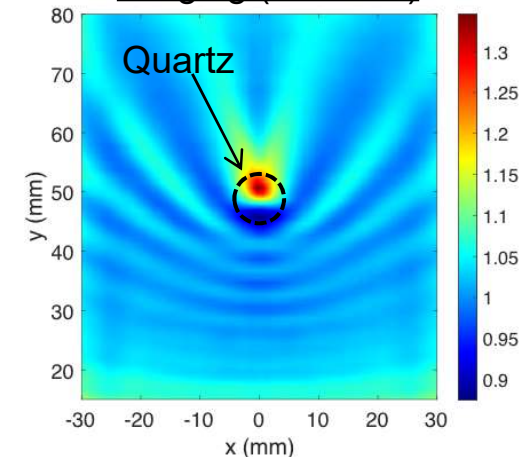
$$\mathbf{k}^*(\bar{\mathbf{x}}, f) = \frac{\sum_{\mathbf{k}} |S(\bar{\mathbf{x}}, f, \mathbf{k})| |\mathbf{k}|}{\sum_{\mathbf{k}} |S(\bar{\mathbf{x}}, f, \mathbf{k})|}$$

$$|\mathbf{k}| = \sqrt{k_x^2 + k_y^2}$$

Maximum intensity wavenumber imaging (120 kHz)



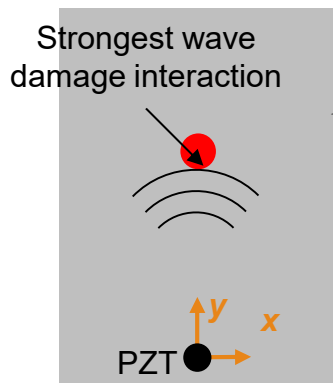
Weighted sum wavenumber imaging (120 kHz)



Actuator network imaging

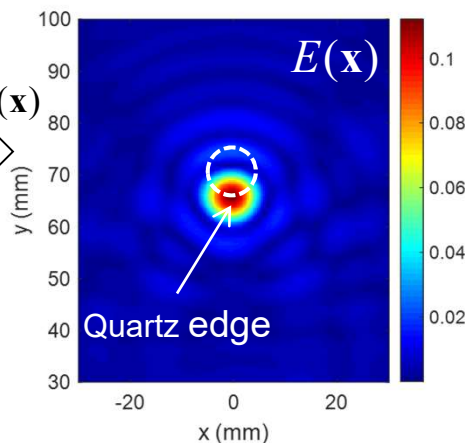
- ❑ With the previous one actuator step, only certain side/direction of the damage can be illuminated by waves with strong energy
- ❑ The strongest wave damage interaction happens at the energy illuminated side or direction

Single actuator scheme



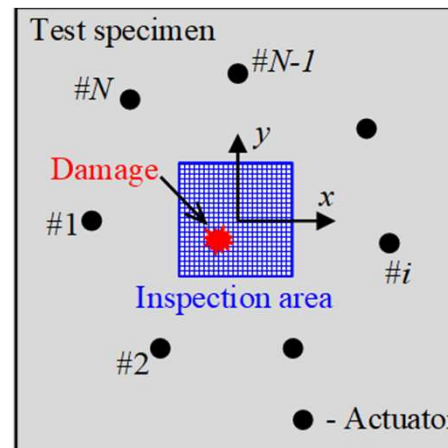
$$p(\mathbf{x}) = E(\mathbf{x})$$

Filtering reconstruction imaging result



- ❑ Actuator takes turn to excite signals and corresponding wavefield is recorded
- ❑ Waves can illuminate the inspected damage from all directions
- ❑ More wave-damage interaction will be captured

Actuator network scheme

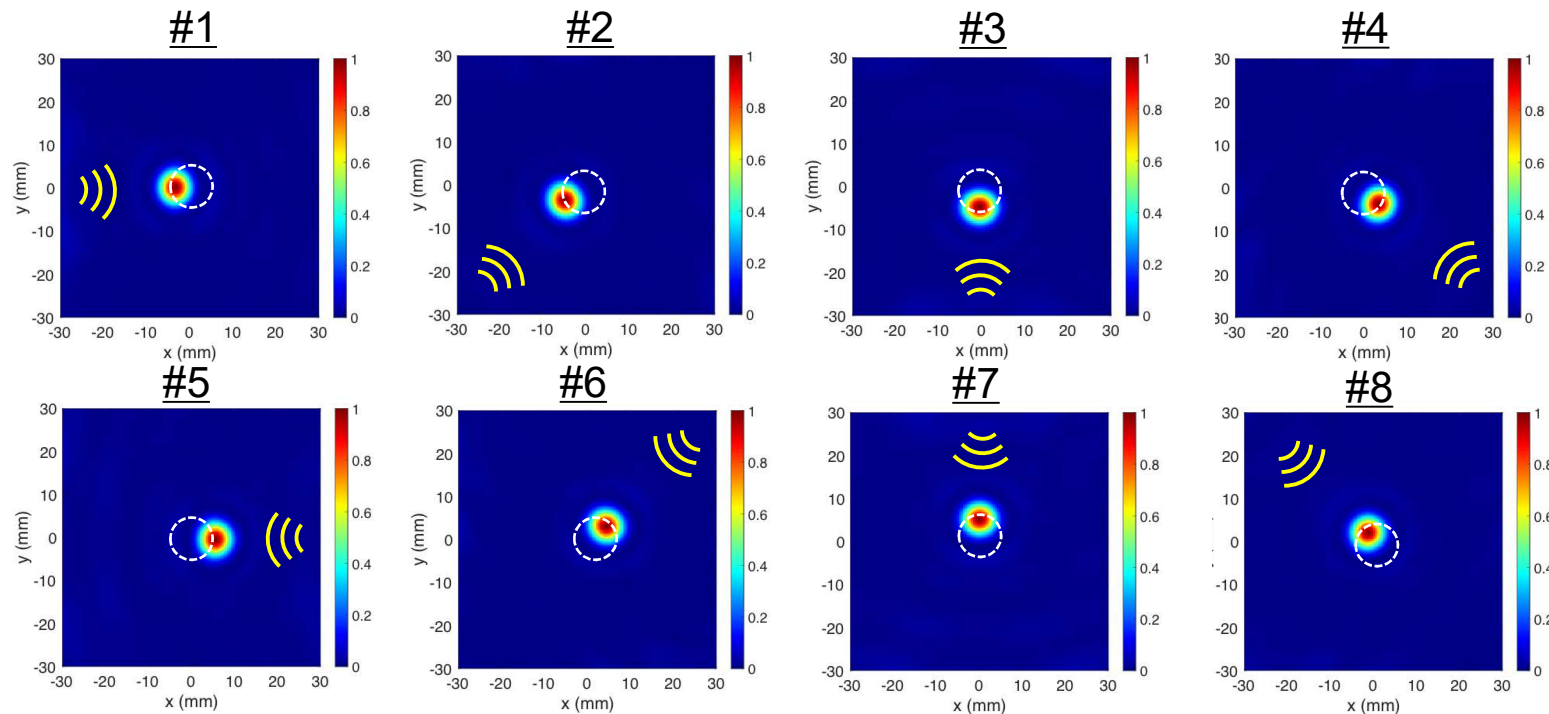


$$p_n(\mathbf{x}) = \begin{cases} E(\mathbf{x}) \\ \mathbf{k}^*(\mathbf{x}) \end{cases}$$

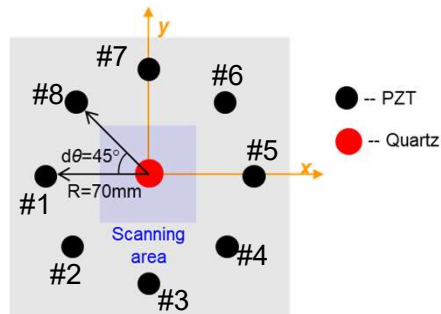
$$P(\mathbf{x}) = \frac{1}{N} \sum_{n=1}^N \frac{p_n(\mathbf{x})}{\max(p_n(\mathbf{x}))}$$

(Yu et al, 2019)

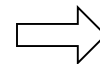
Synthetic imaging through filtering reconstruction



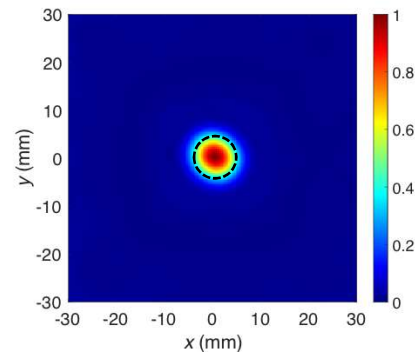
Only part of the profile is quantified



$$P(\mathbf{x}) = \frac{1}{N} \sum_{n=1}^N \frac{p_n(\mathbf{x})}{\max(p_n(\mathbf{x}))}$$



Synthetic imaging result

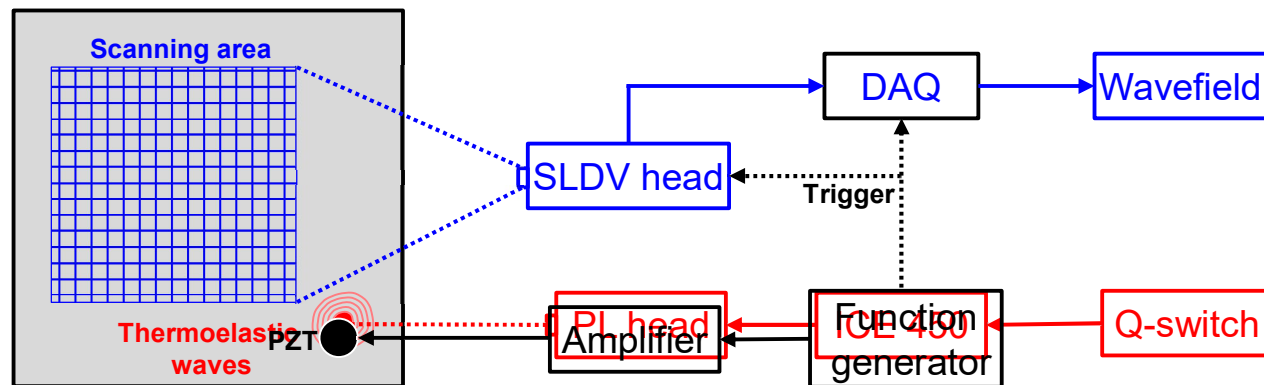


Full profile quantified

(US patent pending)

Part I: Lamb wave NDE/SHM system and methodology development

Noncontact/remote PL-SLDV laser system development

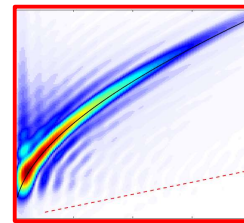


Noncontact PL-SLDV system development

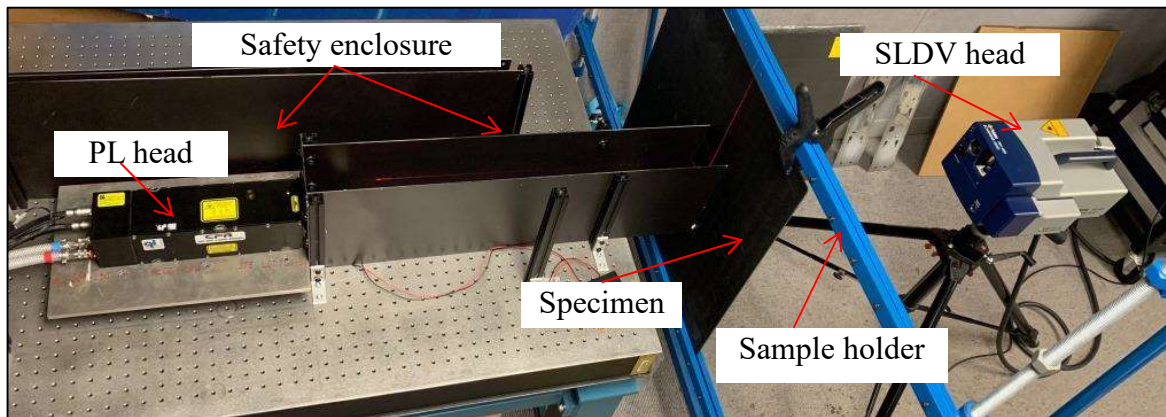


- ❑ Actuation: by Quantel CFR400 Nd:YAG pulsed laser (Q-switch)
 - 100 mJ energy
 - ~ 7 mm beam diameter
 - 0.7 mm thick aluminum foil bonded on the excitation surface
- ❑ Sensing: by Polytech PSV-400 SLDV system
 - 10 averages

Aluminum foil

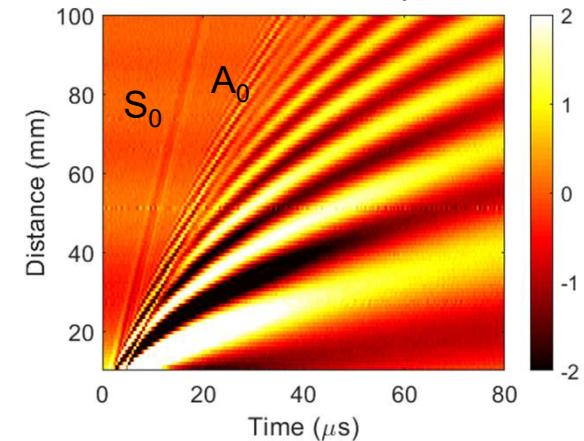


Laboratory setup of PL-SLDV system

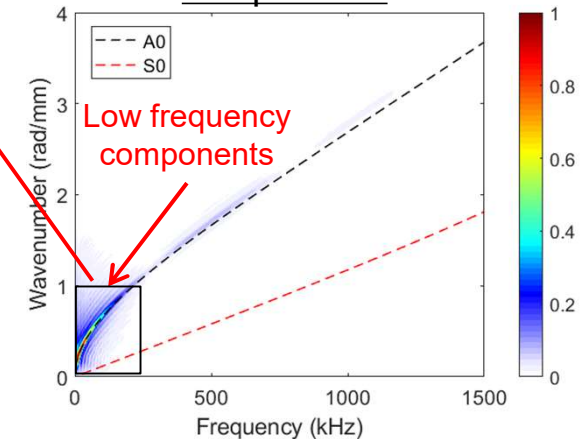


(Ma and Yu, 2020)

Wavefield obtained with SLDV line scan 10 to 100 mm at 0.5 mm space resolution on a 1 mm aluminum plate



f-k spectrum



Proof of concept study on an aluminum plate



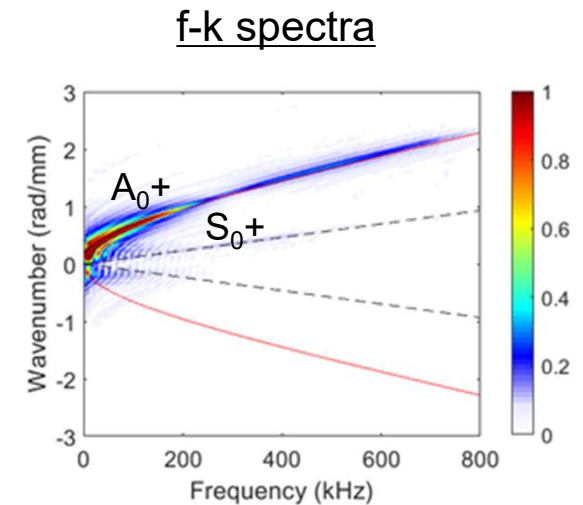
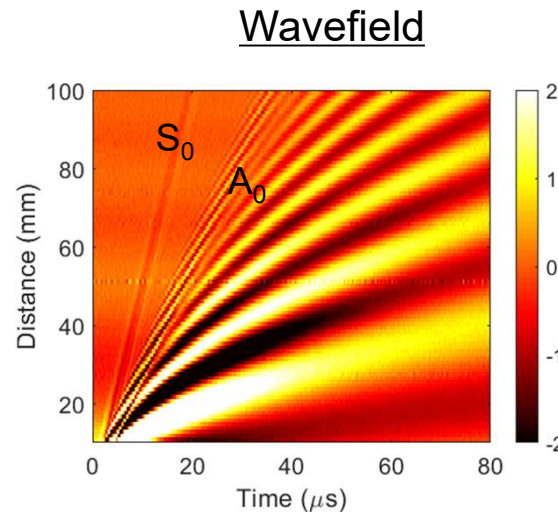
1D inspection

- ❑ Specimen: 1 mm aluminum 2024-T3 plate
 - Pristine
 - Damage: surface bonded quartz rod at 70 mm away from the excitation
- ❑ Sensing: 10 to 100 mm away from the excitation

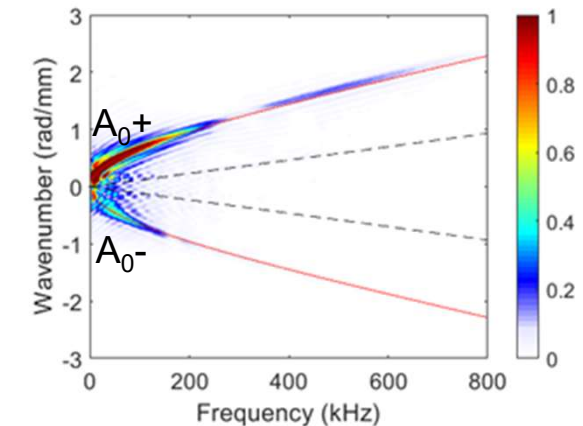
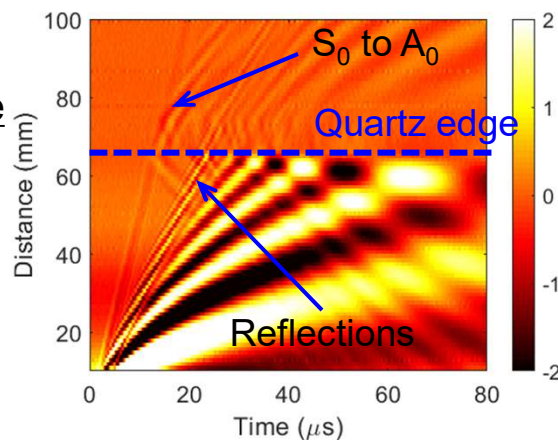
Bonded quartz



Pristine plate

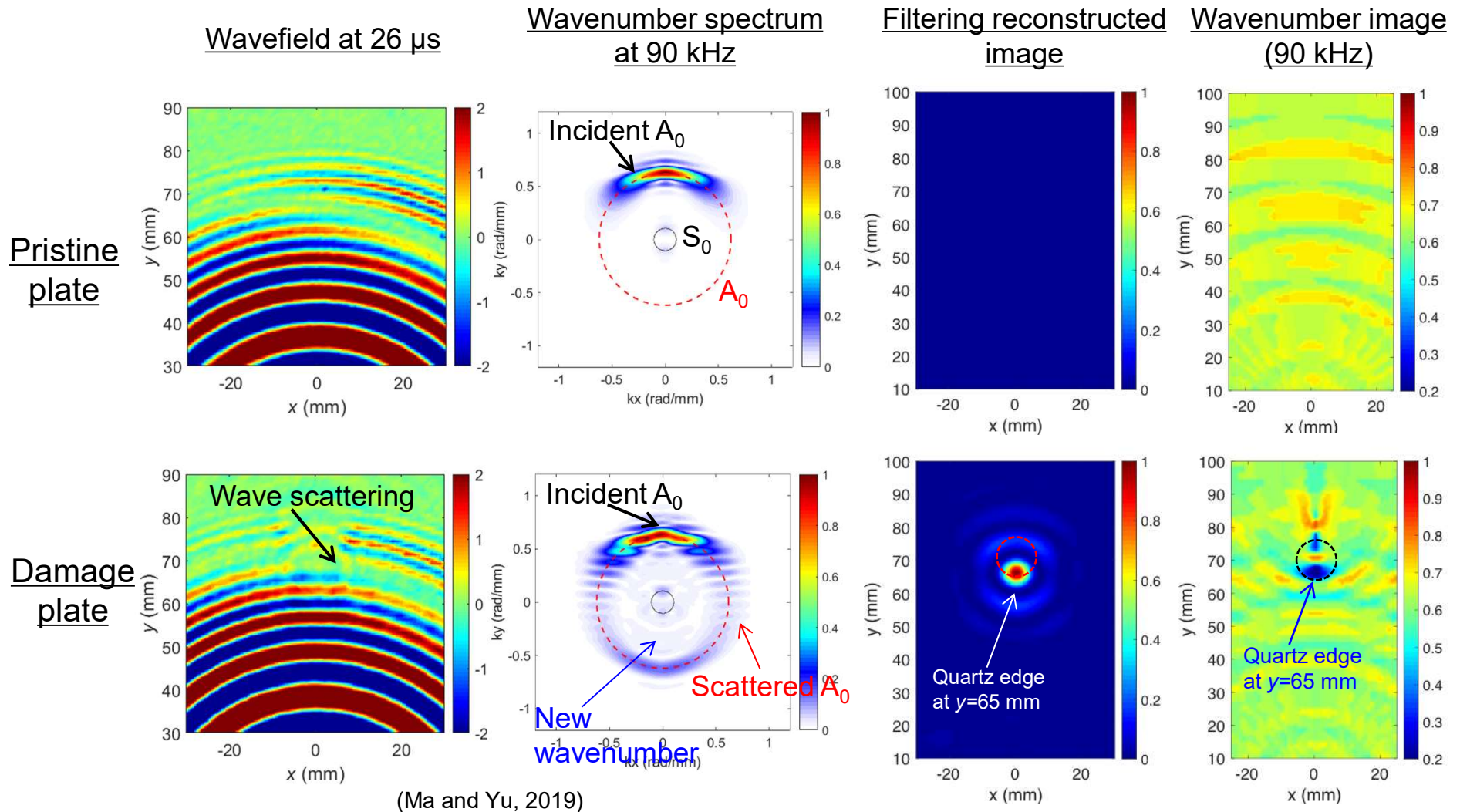


Damage plate



(Ma and Yu, 2019)

2D inspection: wavefield analysis results

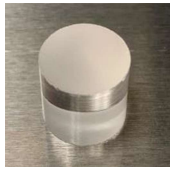


On a composite plate



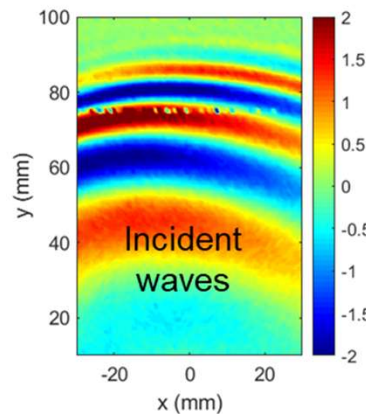
- Specimen: 2.54 mm thick plate 8-ply quasi-isotropic CFRP composite plate with layup $[0,45,90,-45]_s$

Bonded quartz

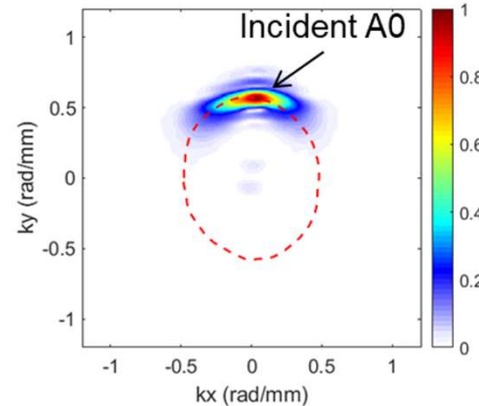


Pristine plate

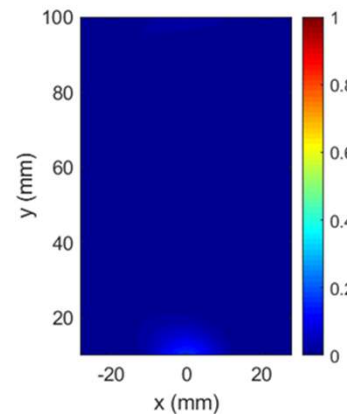
Wavefield



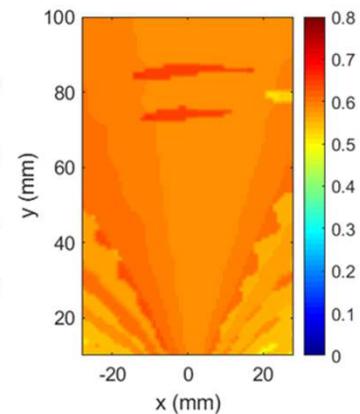
Wavenumber spectrum at 90 kHz



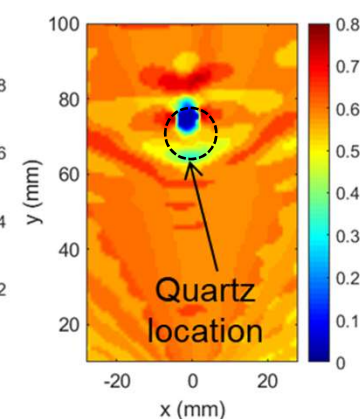
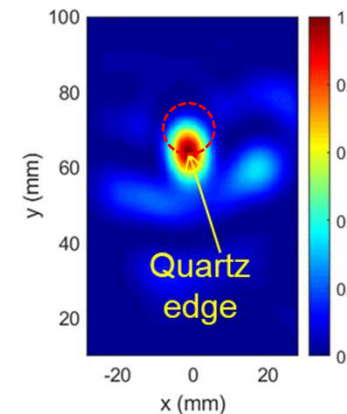
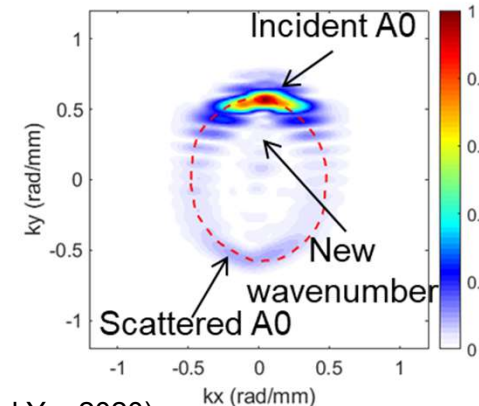
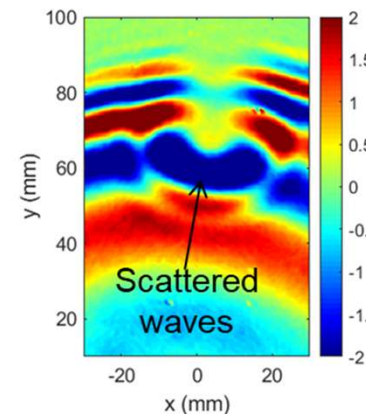
Filtering reconstructed image



Wavenumber image (90 kHz)



Damage plate



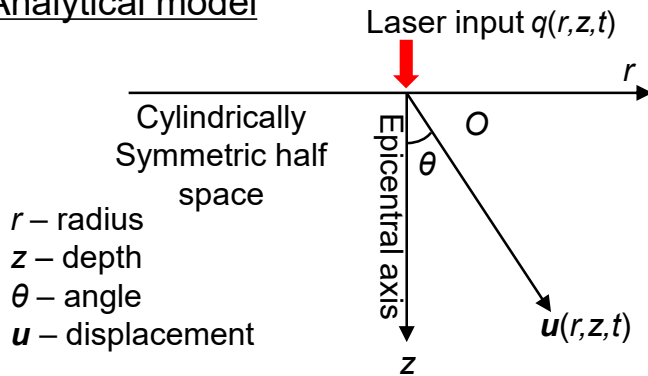
(Ma and Yu, 2020)

Analytical study of laser generated waves

Excitation energy E_i effect

Laser beam radius r_G effect

□ Analytical model



□ Governing equations of thermo-elastic field

$$\nabla^2 T - \frac{1}{\kappa} \cdot \frac{\partial T}{\partial t} - \frac{1}{c_H^2} \cdot \frac{\partial^2 T}{\partial t^2} = -\frac{q}{k}$$

$$\nabla^2 \phi - \frac{1}{c_L^2} \ddot{\phi} = \beta_0 T \quad \text{with} \quad a^2 = \frac{1}{c_L^2}, b^2 = \frac{1}{c_S^2}$$

$$\nabla^2 \psi - \frac{1}{c_S^2} \ddot{\psi} = 0$$

(Arias and Achenbach, 2003)

q – laser heat source density

T – temperature field

κ – thermal conductivity

k – thermal diffusivity

τ_R – thermal relaxation constant

$c_H = \sqrt{\kappa/\tau_R}$ – heat wave speed

$c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}}$ – longitudinal wave speed

$c_S = \sqrt{\frac{\mu}{\rho}}$ – shear wave speed

λ, μ – Lamé constants

□ Displacement and stress in terms of potential

$$u_r = \frac{\partial \phi}{\partial r} + \frac{\partial^2 \psi}{\partial r \partial z} = \frac{\partial}{\partial r} \left(\phi + \frac{\partial \psi}{\partial z} \right), \quad u_z = \frac{\partial \phi}{\partial z} - \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right)$$

$$\sigma_{zz} = -\beta_0 (\lambda + 2\mu) T + \lambda \nabla^2 \phi + 2\mu \frac{\partial}{\partial z} \left(\frac{\partial \phi}{\partial z} - \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right) \right)$$

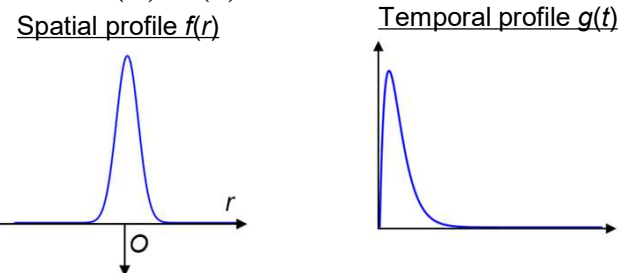
$$\sigma_{rz} = \mu i \left[\frac{\partial}{\partial z} \left(\frac{\partial}{\partial r} \left(\phi + \frac{\partial \psi}{\partial z} \right) \right) + \frac{\partial}{\partial r} \left(\frac{\partial \phi}{\partial z} - \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right) \right) \right]$$

□ Laser input expression

$$q(r, t, z) = E_i (1 - R_i) \gamma e^{-\gamma z} f(r) g(t)$$

$$f(r) = \frac{1}{\sqrt{2\pi}} \frac{2}{r_G} e^{-\frac{2r^2}{r_G^2}}$$

$$g(t) = \frac{t}{\tau^2} e^{-\frac{t}{\tau}}$$



Solving the governing equations

□ Governing equations of thermo-elastic field

$$\nabla^2 T - \frac{1}{\kappa} \cdot \frac{\partial T}{\partial t} - \frac{1}{c_H^2} \cdot \frac{\partial^2 T}{\partial t^2} = -\frac{q}{k}$$

$$\nabla^2 \phi - \frac{1}{c_L^2} \ddot{\phi} = \beta_0 T$$

$$\nabla^2 \psi - \frac{1}{c_S^2} \ddot{\psi} = 0$$

Laplace transform and
Hankel transform

$$a^2 = \frac{1}{c_L^2}, b^2 = \frac{1}{c_S^2}, \beta_0 = \frac{3\lambda + 2\mu}{\lambda + 2\mu} \alpha$$

□ Boundary conditions (stress free surface)

$$\left. \frac{\partial T}{\partial z} \right|_{z=0} = 0$$

$$\left. \sigma_{zz} \right|_{z=0} = -\beta_0 (\lambda + 2\mu) T + \lambda \nabla^2 \phi + 2\mu \frac{\partial}{\partial z} \left(\frac{\partial \phi}{\partial z} - \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right) \right) \Big|_{z=0} = 0$$

$$\left. \sigma_{rz} \right|_{z=0} = \mu \left[\frac{\partial}{\partial z} \left(\frac{\partial}{\partial r} \left(\phi + \frac{\partial \psi}{\partial z} \right) \right) + \frac{\partial}{\partial r} \left(\frac{\partial \phi}{\partial z} - \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right) \right) \right] \Big|_{z=0} = 0$$

$$\left(p^2 + a^2 s^2 + \frac{s}{\kappa} \right) \tilde{T} - \frac{\partial^2 \tilde{T}}{\partial z^2} = \frac{\tilde{q}}{k}$$

$$\left(p^2 + a^2 s^2 \right) \tilde{\phi} - \frac{\partial^2 \tilde{\phi}}{\partial z^2} = -\beta_0 \tilde{T}$$

$$\left(p^2 + b^2 s^2 \right) \tilde{\psi} - \frac{\partial^2 \tilde{\psi}}{\partial z^2} = 0$$

$$\left. \frac{\partial \tilde{T}}{\partial z} \right|_{z=0} = 0$$

$$\left. \tilde{\sigma}_{zz} \right|_{z=0} = -\beta_0 (\lambda + 2\mu) \tilde{T} + (\lambda + 2\mu) \left(\frac{\partial^2 \tilde{\phi}}{\partial z^2} - \lambda p^2 \tilde{\phi} + 2\mu p^2 \frac{\partial \tilde{\psi}}{\partial z} \right) \Big|_{z=0} = 0$$

$$\left. \tilde{\sigma}_{rz} \right|_{z=0} = \mu i p \left(2 \frac{\partial \tilde{\phi}}{\partial z} + \frac{\partial^2 \tilde{\psi}}{\partial z^2} + p^2 \tilde{\psi} \right) \Big|_{z=0} = 0$$

□ Solved potential in the transformed domain

$$\tilde{T} = \frac{Q\gamma^2}{\xi^2 - \gamma^2} \left(\frac{1}{\gamma} e^{-\gamma z} - \frac{1}{\xi} e^{-\xi z} \right);$$

$$\tilde{\psi} = \frac{\beta_0 Q\gamma^2}{\gamma^2 - \xi^2} \frac{2\zeta(\eta^2 + p^2)}{(\eta^2 + p^2)^2 - 4\zeta\eta p^2} \left[\frac{\kappa}{s} \left(\frac{1}{\zeta} - \frac{1}{\xi} \right) + \frac{1}{\zeta^2 - \gamma^2} \left(\frac{1}{\zeta} - \frac{1}{\gamma} \right) \right] e^{-\eta z}$$

$$\tilde{\phi} = \frac{\beta_0 Q\gamma^2}{\gamma^2 - \xi^2} \left\{ \frac{(\eta^2 + p^2)^2}{(\eta^2 + p^2)^2 - 4\zeta\eta p^2} \left[\frac{\kappa}{s} \left(\frac{1}{\zeta} - \frac{1}{\xi} \right) + \frac{1}{\zeta^2 - \gamma^2} \left(\frac{1}{\zeta} - \frac{1}{\gamma} \right) \right] e^{-\zeta z} + \frac{\kappa}{s} \left(\frac{1}{\xi} e^{-\xi z} - \frac{1}{\zeta} e^{-\zeta z} \right) + \frac{1}{\zeta^2 - \gamma^2} \left(\frac{1}{\gamma} e^{-\gamma z} - \frac{1}{\zeta} e^{-\zeta z} \right) \right\}$$

Analytical solution: temperature and displacement

□ Displacement in terms of potential

$$\begin{aligned}
 u_r &= \frac{\partial \phi}{\partial r} + \frac{\partial^2 \psi}{\partial r \partial z} = \frac{\partial}{\partial r} \left(\phi + \frac{\partial \psi}{\partial z} \right) \\
 u_z &= \frac{\partial \phi}{\partial z} - \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right)
 \end{aligned}
 \xrightarrow[\substack{a^2 = \frac{1}{c_L^2}, b^2 = \frac{1}{c_S^2}, \beta_0 = \frac{3\lambda + 2\mu}{\lambda + 2\mu} \alpha}]{\text{Laplace transform and Hankel transform}}
 \begin{aligned}
 \tilde{u}_r &= -p \left(\tilde{\phi} + \frac{\partial \tilde{\psi}}{\partial z} \right) \\
 \tilde{u}_z &= \frac{\partial \tilde{\phi}}{\partial z} + p^2 \tilde{\psi}
 \end{aligned}
 \begin{array}{c} \tilde{\psi} \\ \leftarrow \\ \tilde{\phi} \end{array}$$

$$\begin{aligned}
 \tilde{u}_r &= -ip \left(A_1 e^{-\zeta z} - \frac{2\zeta \eta}{\eta^2 + p^2} A_1 e^{-\eta z} + A_2 \right) \\
 \tilde{u}_z &= -\zeta A_1 e^{-\zeta z} + \frac{2\zeta p^2}{\eta^2 + p^2} A_1 e^{-\eta z} + A_3
 \end{aligned}
 \quad \text{with} \quad
 \begin{aligned}
 A_1 &= \frac{\beta_0 Q \gamma^2}{\gamma^2 - \xi^2} \frac{(\eta^2 + p^2)^2}{(\eta^2 + p^2)^2 - 4\zeta \eta p^2} \left[\frac{\kappa}{s} \left(\frac{1}{\xi} - \frac{1}{\zeta} \right) + \frac{1}{\zeta^2 - \gamma^2} \left(\frac{1}{\zeta} - \frac{1}{\gamma} \right) \right] \\
 A_2 &= \frac{\beta_0 Q \gamma^2}{\gamma^2 - \xi^2} \left[\frac{\kappa}{s} \left(\frac{1}{\xi} e^{-\xi z} - \frac{1}{\zeta} e^{-\zeta z} \right) + \frac{1}{\zeta^2 - \gamma^2} \left(\frac{1}{\gamma} e^{-\gamma z} - \frac{1}{\zeta} e^{-\zeta z} \right) \right] \\
 A_3 &= \frac{\beta_0 Q \gamma^2}{\gamma^2 - \xi^2} \left[\frac{\kappa}{s} (e^{-\xi z} - e^{-\zeta z}) + \frac{1}{\zeta^2 - \gamma^2} (e^{-\zeta z} - e^{-\gamma z}) \right]
 \end{aligned}$$

□ Surface temperature and displacement field

$$\begin{aligned}
 \tilde{T} \Big|_{z=0} &= \frac{Q \gamma^2 (\gamma^{-1} - \xi^{-1})}{\xi^2 - \gamma^2} \\
 \tilde{u}_z \Big|_{z=0} &= \frac{\beta_0 Q \gamma^2}{\gamma^2 - \xi^2} \frac{(\eta^2 + p^2) b^2 s^2}{(\eta^2 + p^2)^2 - 4\zeta \eta p^2} \left[\frac{\kappa}{s} (\zeta \xi^{-1} - 1) + \frac{1}{\xi^2 - \gamma^2} (\zeta \gamma^{-1} - 1) \right] \\
 \tilde{u}_z \Big|_{z=0} (\gamma \rightarrow \infty) &= \frac{Q \beta_0 \kappa b^2 s (\eta^2 + p^2) (\zeta \xi^{-1} - 1)}{(\eta^2 + p^2)^2 - 4\zeta \eta p^2}
 \end{aligned}
 \xrightarrow[\substack{\text{Inverse Hankel transform} \\ \text{(Abate and Whitt, 2006)}}]{\substack{\text{Inverse Laplace} \\ \text{transform (Guizar-Sicairos and} \\ \text{Gutiérrez-Vega, 2004)}}}
 \boxed{
 \begin{aligned}
 T(r, t) \Big|_{z=0} \\
 u_z(r, t) \Big|_{z=0}
 \end{aligned}
 }$$

$$\begin{aligned}
 Q &= Q_o Q_p Q_s, \quad Q_o = \frac{E_i}{k} (1 - R_i) \\
 Q_p &= H(f(r)) = \frac{1}{\sqrt{2\pi}} e^{-\frac{p^2 r_G^2}{8}} \\
 Q_s &= L(g(t)) = \frac{1}{\tau^2 (s + 1/\tau)^2} \\
 \xi^2 &= p^2 + a^2 s^2 + \frac{s}{\kappa}, \quad \eta^2 = p^2 + b^2 s^2 \\
 \zeta^2 &= p^2 + a^2 s^2, \quad \beta_0 = \frac{3\lambda + 2\mu}{\lambda + 2\mu} \alpha
 \end{aligned}$$

(Truong et al., 2018)

Numerical and experimental parametric study

- ❑ Material: aluminum 2024-T3
- ❑ Experimental setup:
 - Epicenter displacement is measured on 1 mm aluminum plate by SLDV
 - PL excitation with selected energy and focused to selected radius using a point focusing lens
- ❑ Excitation energy E_i : 1.3, 2.6, 3.9, and 5.2 mJ, with $r_G=2$ mm
- ❑ Laser beam radius r_G : 1.5, 2.0, 2.5, and 3.0 mm, with $E_i=3.9$ mJ

➤ Mechanical properties

$$E = 73.1 \text{ GPa}$$

$$\rho = 2780 \text{ kg/m}^3$$

$$\nu = 0.33$$

➤ Laser parameters

$$\tau = 8 \text{ ; laser pulse rise time (ns)}$$

➤ Thermal properties

$$\alpha = 2.32 \times 10^{-5} \text{ ; thermal expansion coefficient (K}^{-1}\text{)}$$

$$k = 121 \text{ ; thermal conductivity (W/m} \cdot \text{K)}$$

$$\kappa = 5 \times 10^{-5} \text{ ; thermal diffusivity (m}^2 \text{ / s)}$$

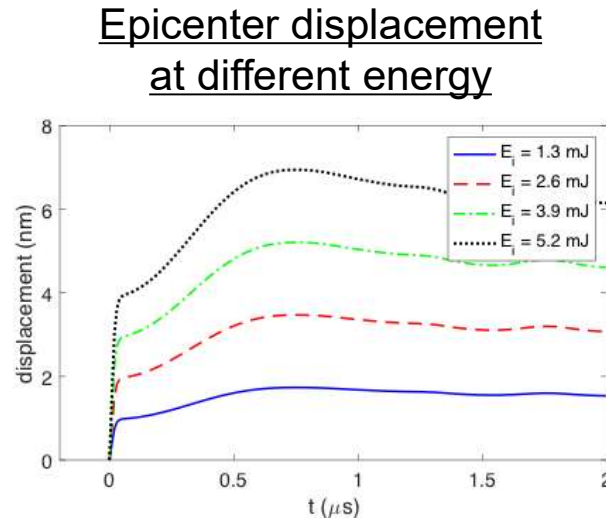
$$R_i = 0.9 \text{ ; reflection index (dimensionless)}$$

$$c_v = 875 \text{ ; specific heat capacity (J/kg} \cdot \text{K)}$$

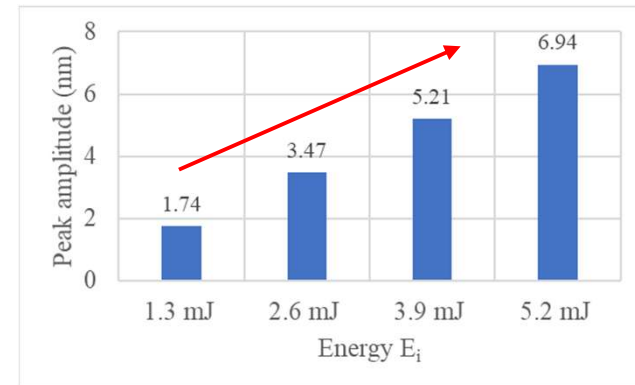
<http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA2024T3>
<https://www.gabrian.com/2024-aluminum-properties/>
<https://refractiveindex.info/?shelf=main&book=Al&page=Rakic>
(Scruby and Drain, 1990)

Comparison of energy E_i effect

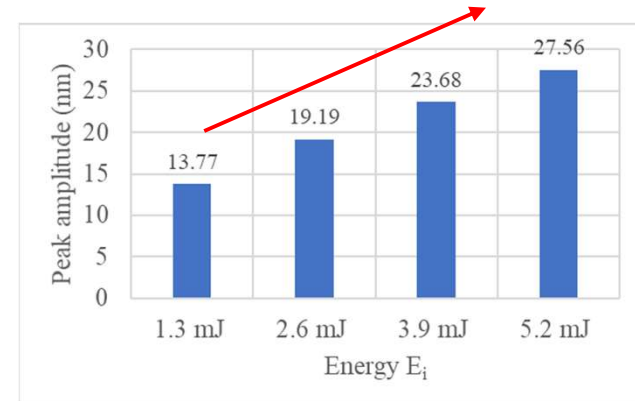
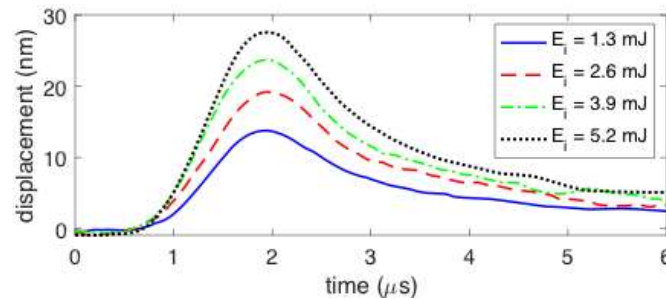
Numerical results



Peak to peak variation with energy change



Experimental results

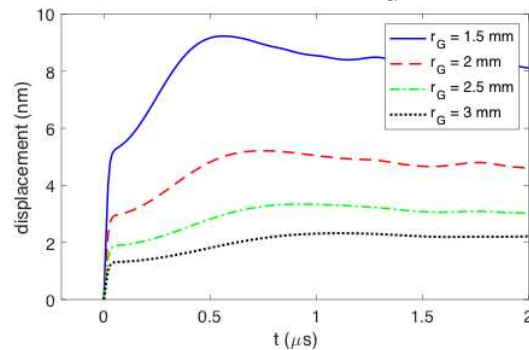


- Both the numerical and experimental results show that the excitation energy increase results in the epicenter displacement increase

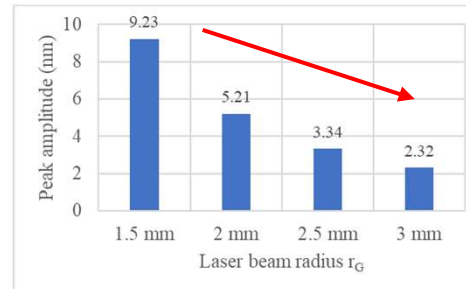
Laser beam radius r_G effect

Numerical results

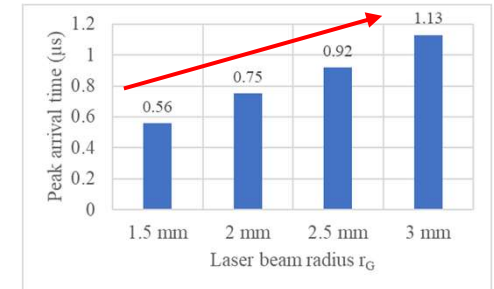
Epicenter displacement at various r_G



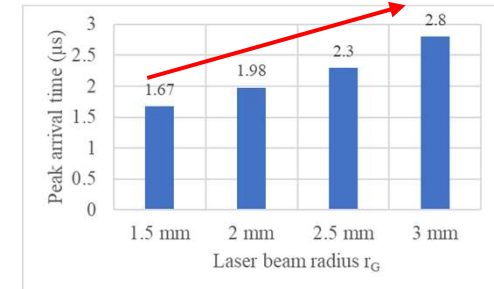
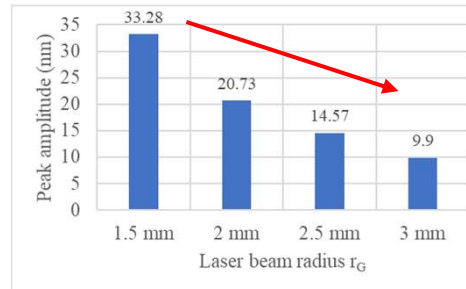
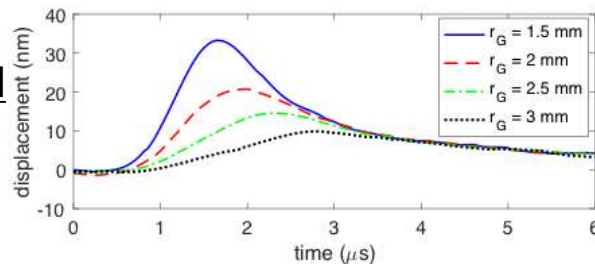
Peak to peak variation



Peak arrival time variation

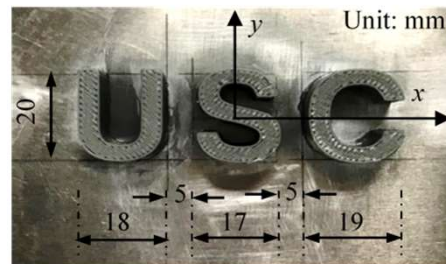
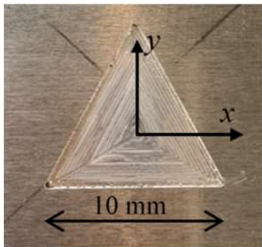


Experimental results



- ❑ Both the numerical and experimental results show that the increase of the laser beam radius results in the epicenter displacement decrease
- ❑ Both results show that the increase of the laser beam radius results in the peak arrival time delay

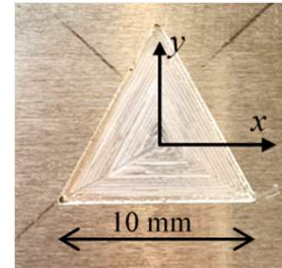
Part II: NDE/SHM applications on aerospace and nuclear structures on aerospace metallic structures



Case 1: complex damage evaluation

- ❑ Specimen: 1 mm aluminum 2024-T3 plate
 - Damage 1: machine milled triangular mass loss
 - Damage 2: bonded letter cluster 'USC'
- ❑ Method: actuator network imaging using the same setup as in the demonstration

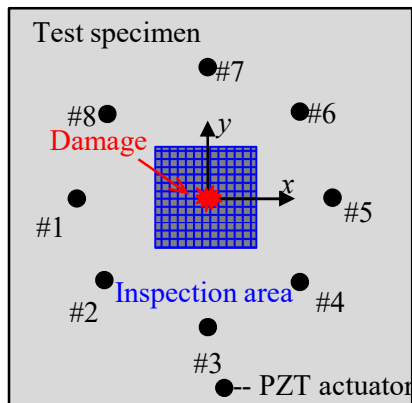
Triangular mass loss



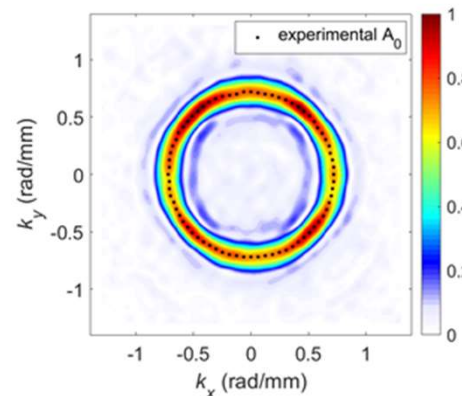
Bonded letter cluster



Actuator network setup



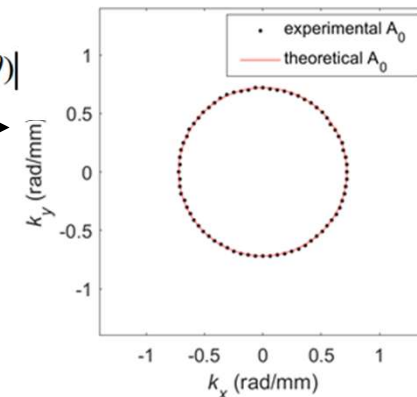
Wavenumber spectrum at 120 kHz
on pristine plate with a PZT
actuator at the origin



$$r(f, \theta) = \arg \max_r |V(f, r, \theta)|$$

$$k_x = r \cos \theta, k_y = r \sin \theta$$

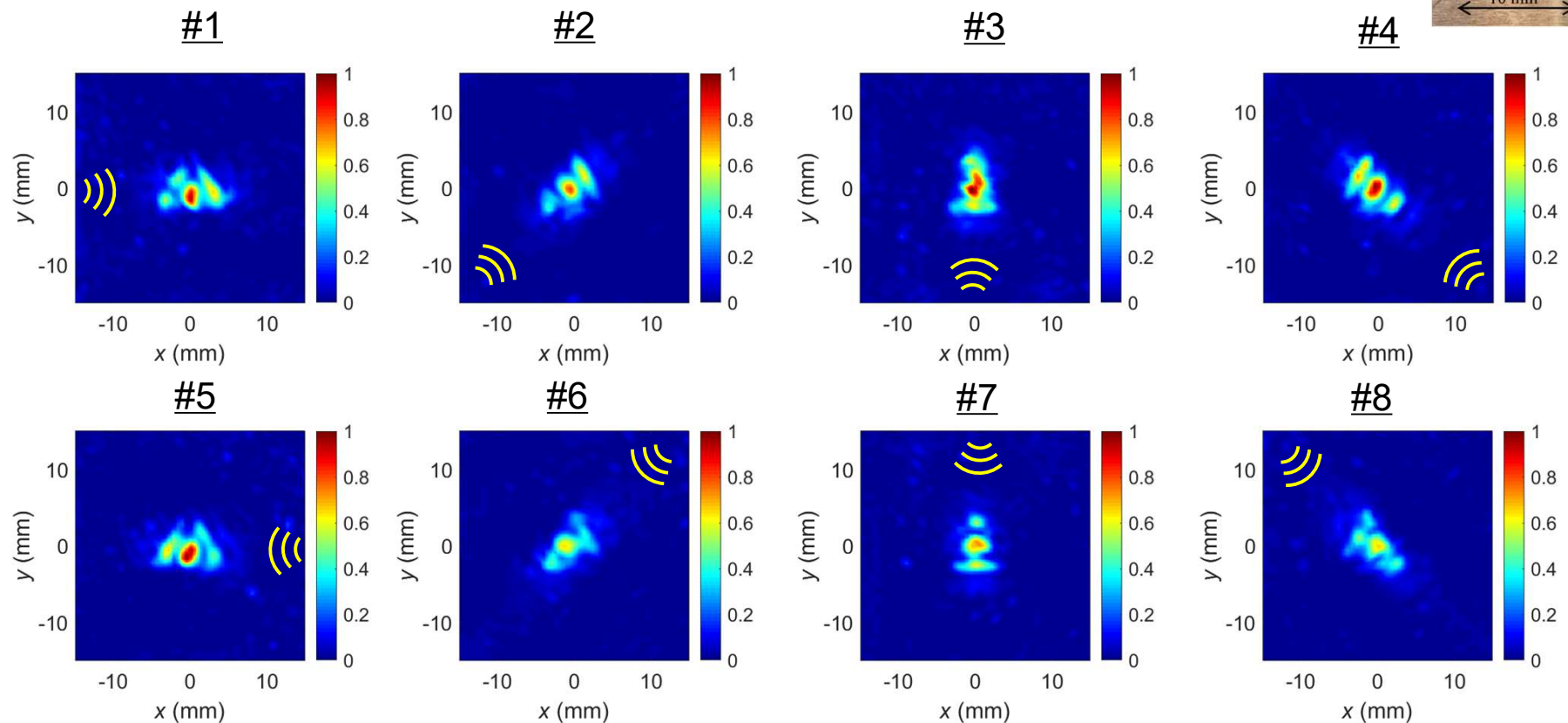
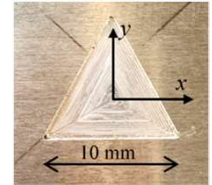
Comparison between the experimental
and theoretical wavenumber curves



(Ma and Yu, 2020)

Triangular mass loss evaluation with single actuator

□ Imaging method: filtering reconstruction imaging

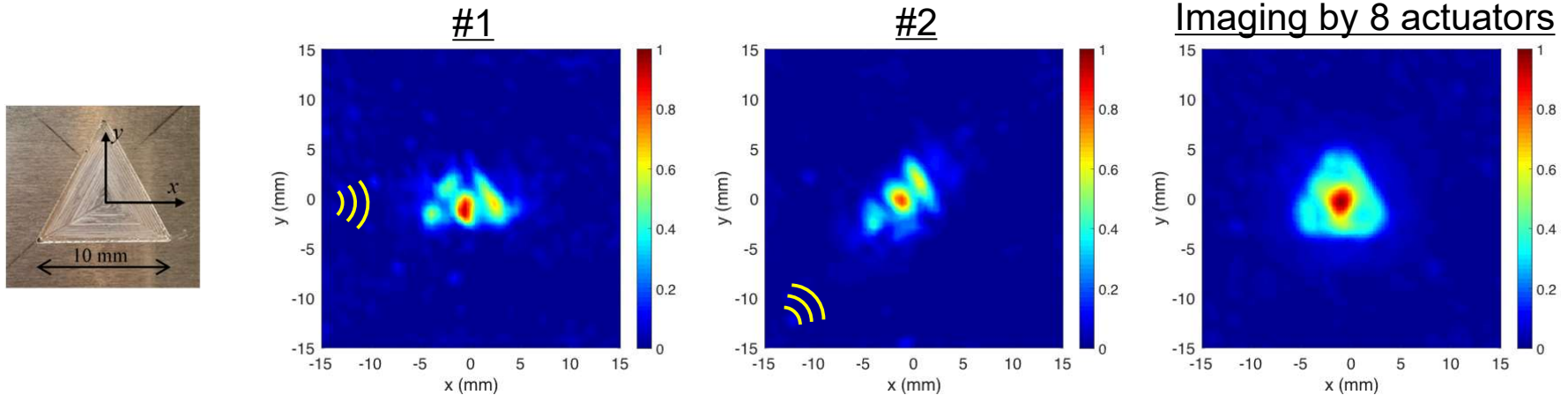


Only part of the profile is quantified

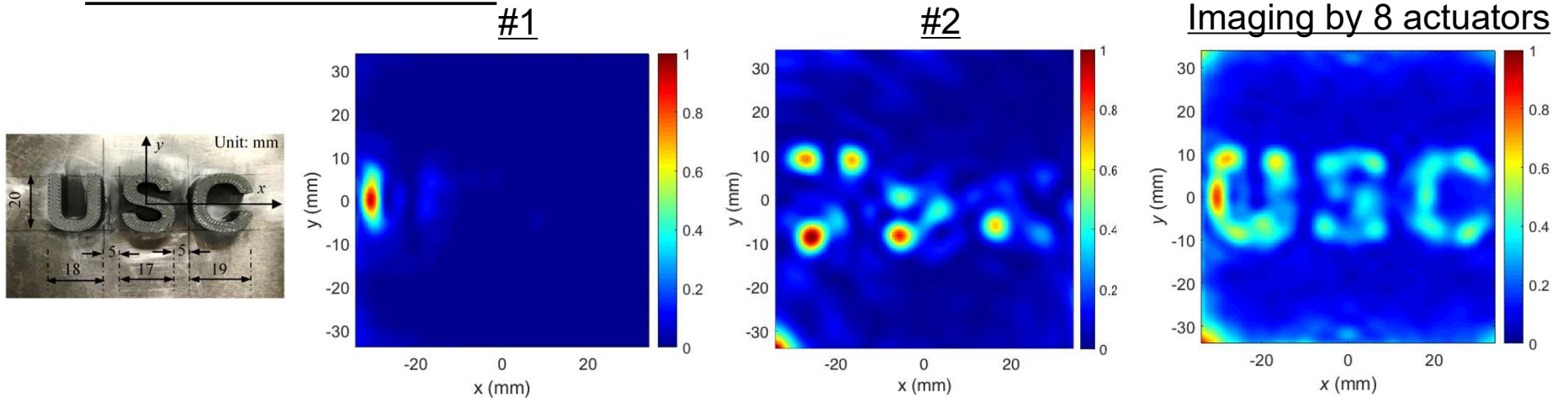
(Ma and Yu, 2020)

Actuator network imaging results

□ Triangular mass loss



□ Bonded letter cluster



(Ma and Yu, 2020)

Case 2: crack quantification

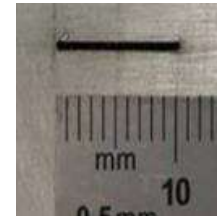
❑ Specimen: 1 mm aluminum 2024-T3 plate

- machine milled notch (0.5 mm wide, 10 mm long)
- “hairline” fatigue crack (1 mm initial hole and total length ~30 mm long)

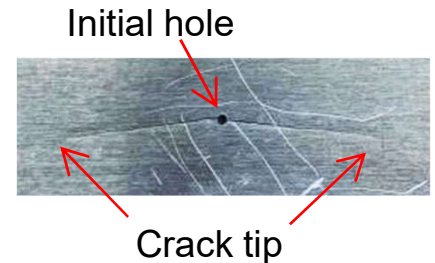
❑ System: noncontact PL-SLDV system

❑ Method: filtering reconstruction imaging

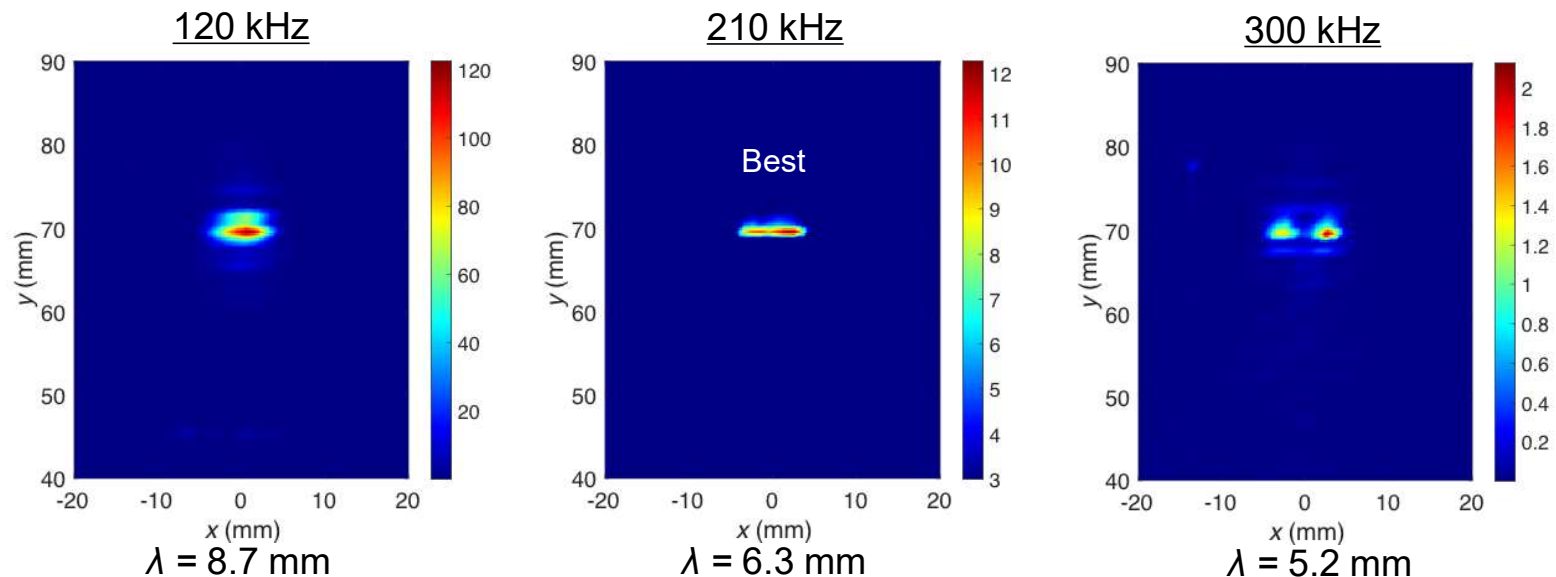
Machine milled notch



Hairline fatigue crack

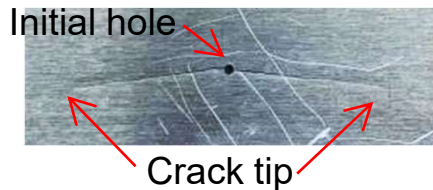


Machine milled notch imaging (frequency study)



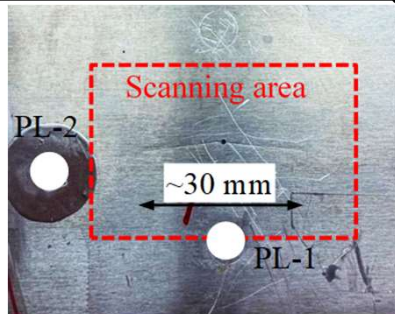
Hairline fatigue crack evaluation (210 kHz)

Hairline fatigue crack



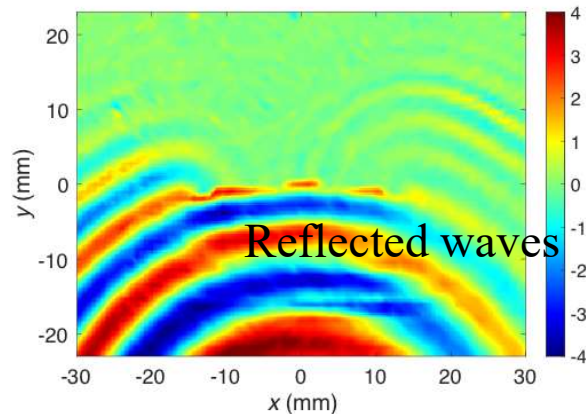
- ❑ Fatigue crack growth was initiated with a 1 mm diameter hole
- ❑ Cyclic fatigue loading is applied at 4 Hz using MTS machine, with the load level between 6.5% to 65% of the yield strength

Actuation and sensing

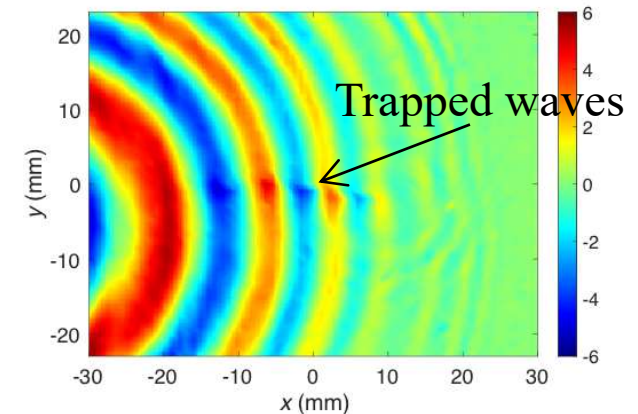


Normal inspection (PL-1)

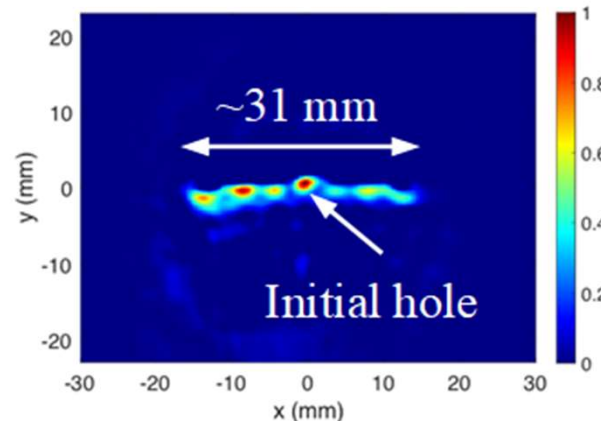
Wavefield



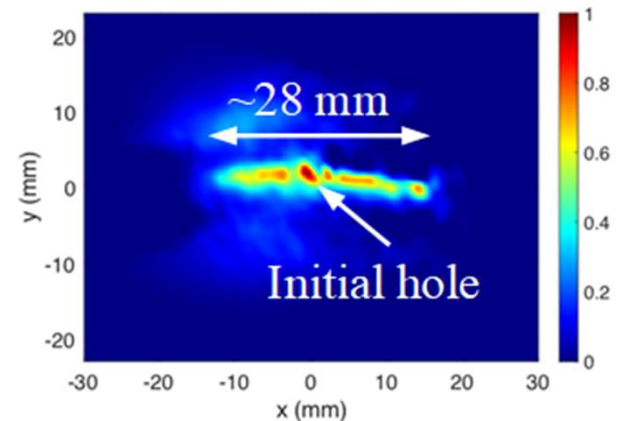
Parallel inspection (PL-2)



Imaging results



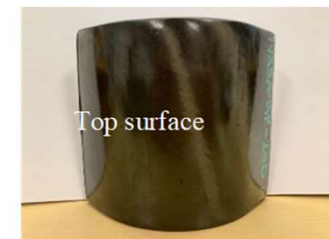
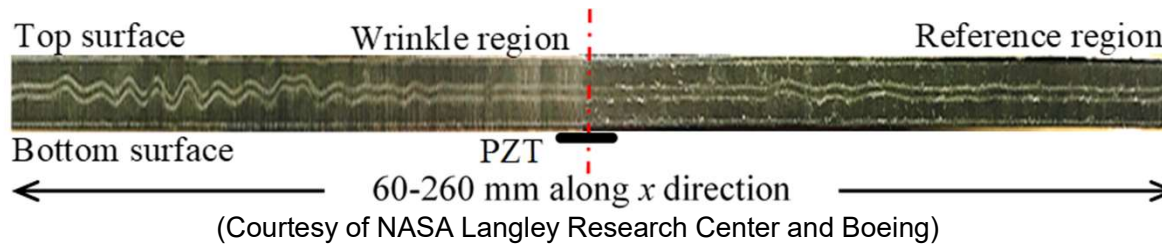
- ❑ Initial hole highlighted, both crack tips are captured
- ❑ total length quantified with ~3.3% error



- ❑ Initial hole highlighted, left tip is not quantified
- ❑ total length quantified with ~6.7% error

Part II: Applications on aerospace and nuclear structures

on aerospace composite structures



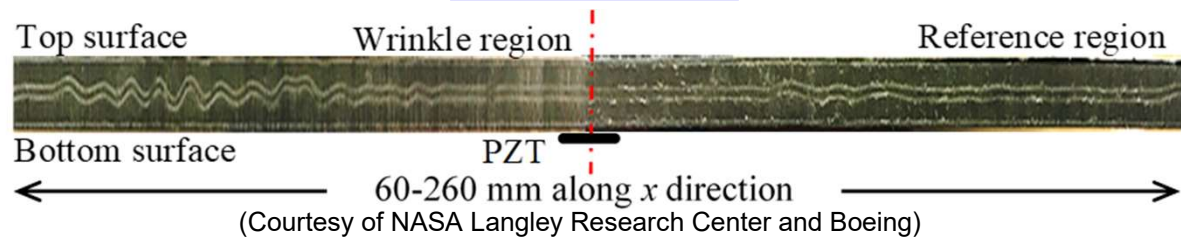
(Courtesy of NASA Langley Research Center and ACP members)

Case 1: wrinkle defect evaluation



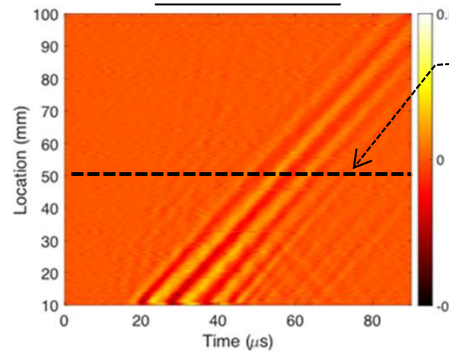
- ❑ Specimen: 20-ply CFRP plate with unknown material properties
- ❑ Inspection system: nonintrusive PZT-SLDV system with honey as PZT couplant and wipe-off reflective spray for SLDV light enhancement
- ❑ Actuation: 3-count toneburst at 50 V_{pp} at 120 kHz or 210 kHz

Thickness view

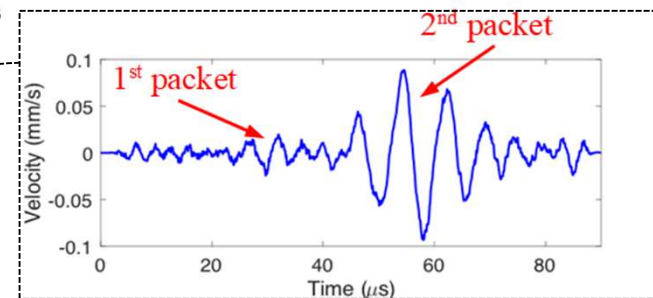


1D inspection results

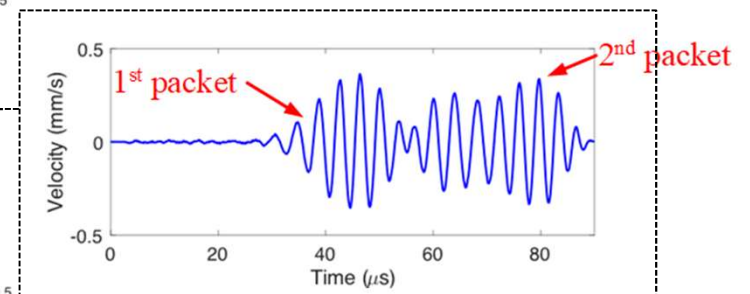
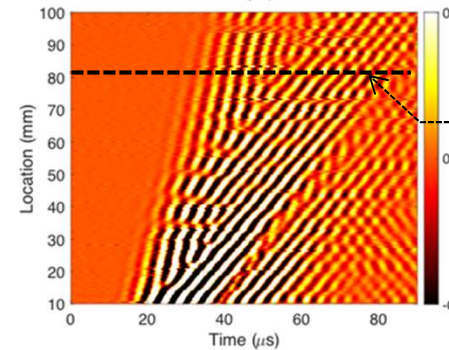
Wavefield



Waveform

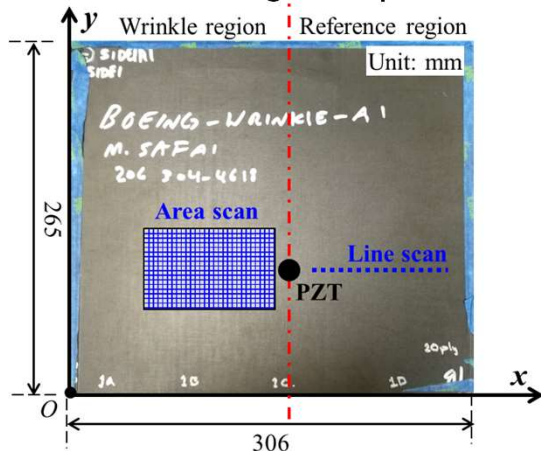


120 kHz



210 kHz

Sensing setup

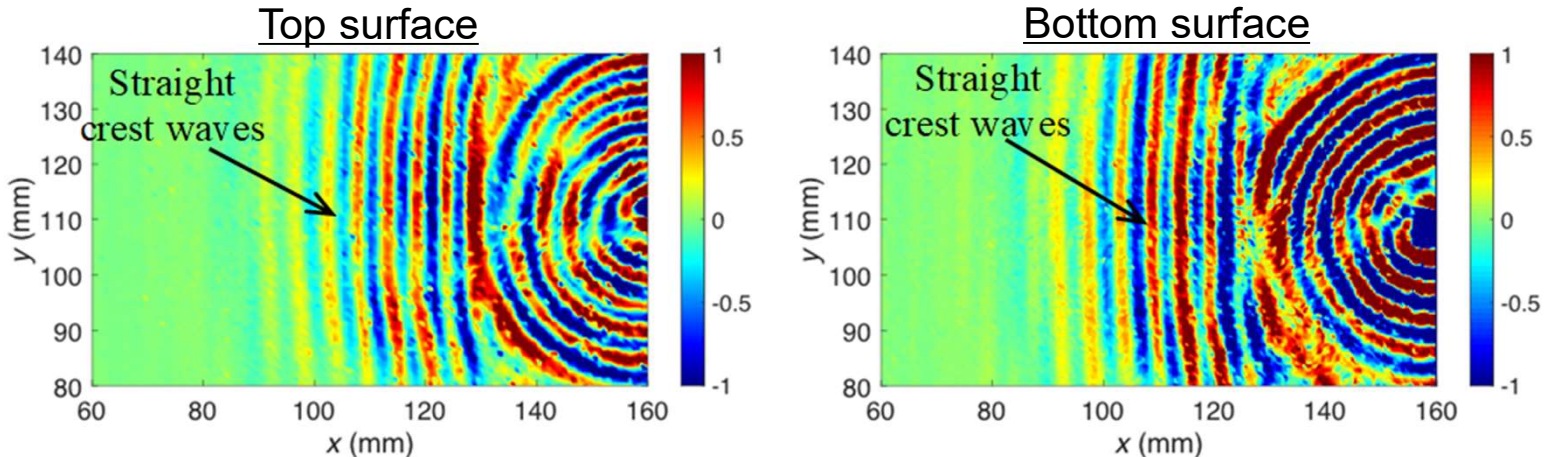


(Courtesy of NASA Langley Research Center and Boeing)

Wavefield analysis and group velocity estimation



Wavefield snapshot at 29 μs



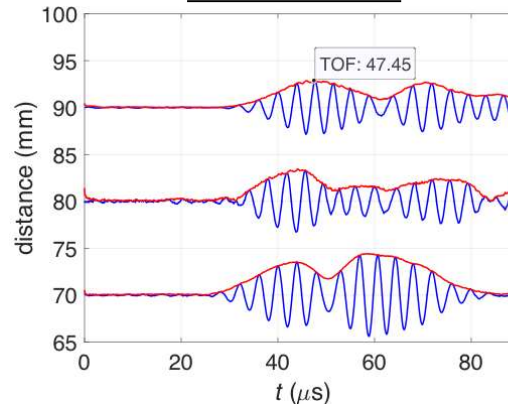
□ Adaptive wavefield imaging method

$$t_{tof}(\mathbf{x}) = \frac{\sqrt{(x-x_0)^2 + (y-y_0)^2}}{c_g}$$

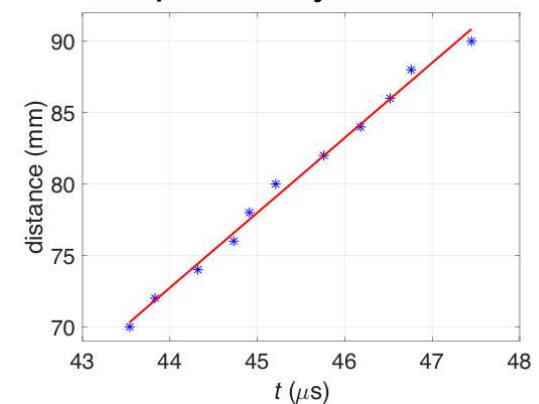
$$v_{1st}(t, \mathbf{x}) = v(t, \mathbf{x})W_{tof}(t)$$

$$v_{1st}^{mag}(t, \mathbf{x}) = \max |v_{1st}(t, \mathbf{x})|$$

Waveforms



Group velocity estimation

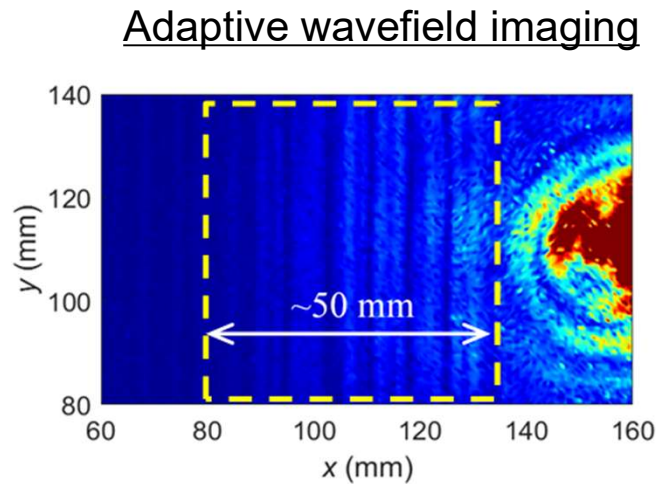


$$c_g^{1st} \approx 5.249 \text{ mm}/\mu\text{s}$$

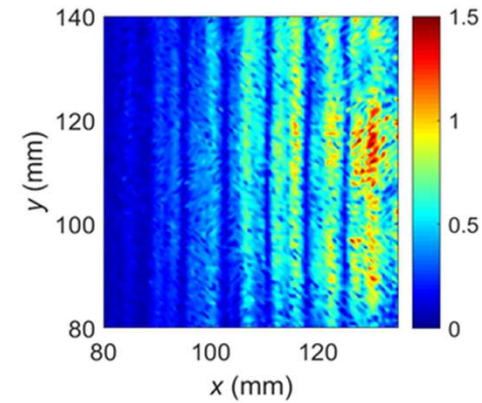
Adaptive wavefield imaging results



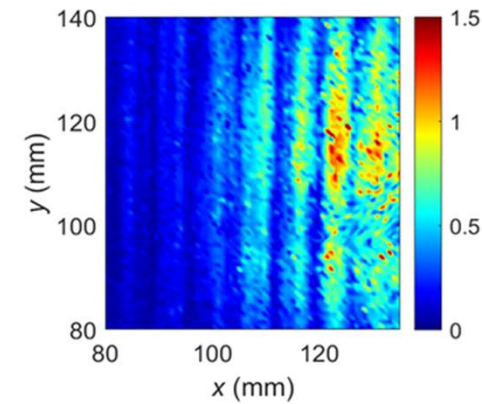
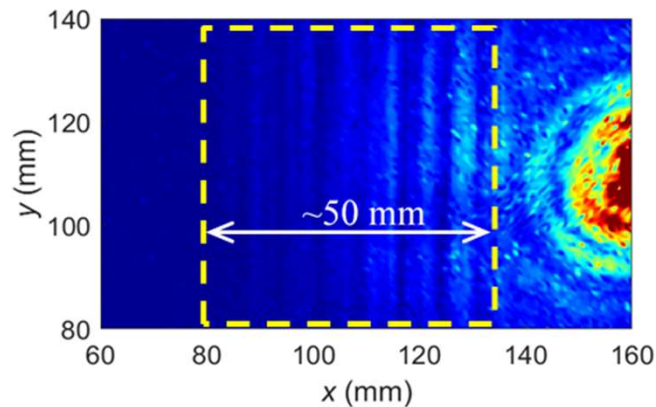
Top
surface



Zoom in results



Bottom
surface



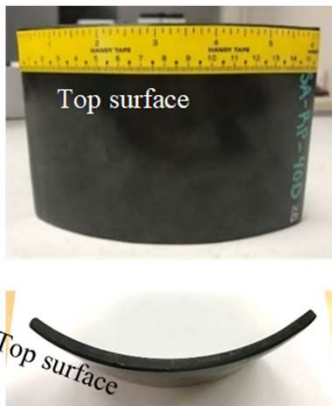
(Courtesy of NASA Langley Research Center and Boeing)

Detected wrinkle ranges: 80-130
mm along x direction

Case 2: delamination evaluation in curved plates

- ❑ Specimen: three composite plates with different radius of curvature (R)
- ❑ Imaging method: weighted sum wavenumber imaging method
- ❑ Actuation: 3-count toneburst at $50 V_{pp}$ at 150 kHz with two excitations at the center of each wing
- ❑ Sensing: 2D area scans in the accessible areas on both surfaces of the plate
 - The scanning angle effect due to the curvature is neglected

Specimen #1
($R=40$ mm)



Specimen #2
($R=20$ mm)

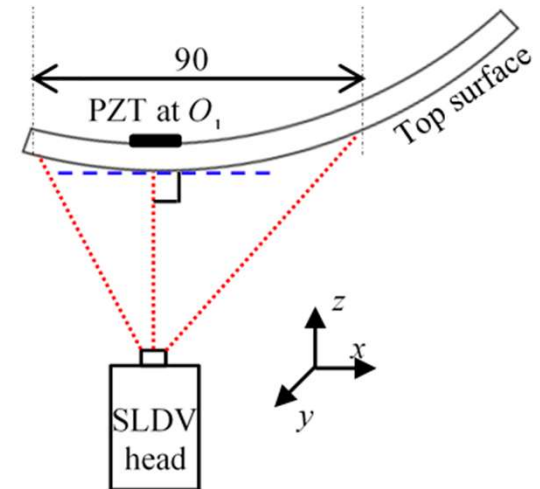
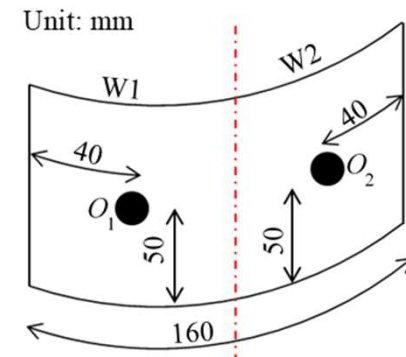


Specimen #3
($R=10$ mm)

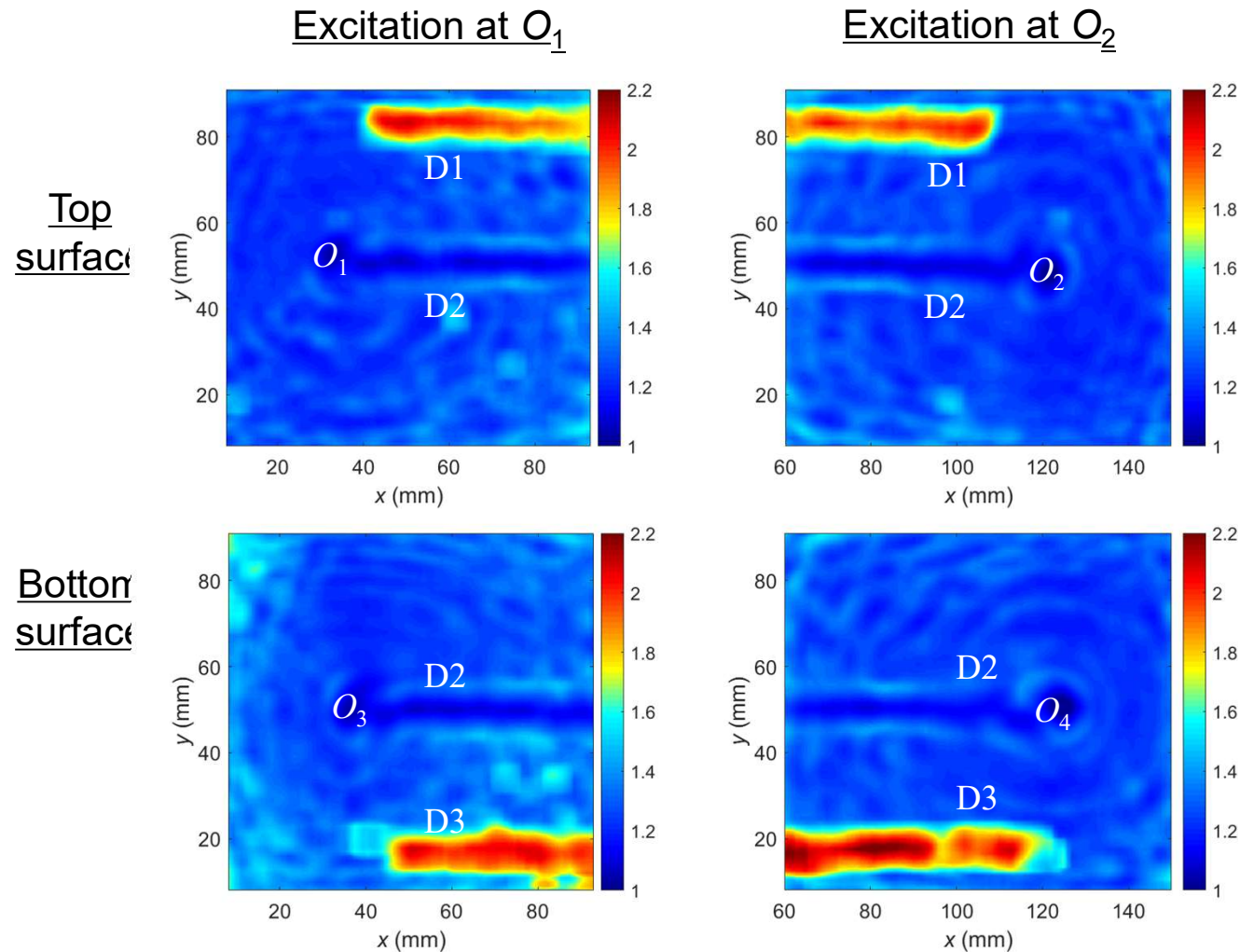


(Courtesy of NASA Langley Research Center and ACP members)

Actuation and sensing setup



Wavenumber imaging: Sample #1 ($R=40$ mm)



Total three delamination in the plate: D1, D2, and D3
The delamination exists in the range 40-110 mm along x direction
D1 is close to top surface, while D3 is close to bottom surface.
D2 might be in the middle plane

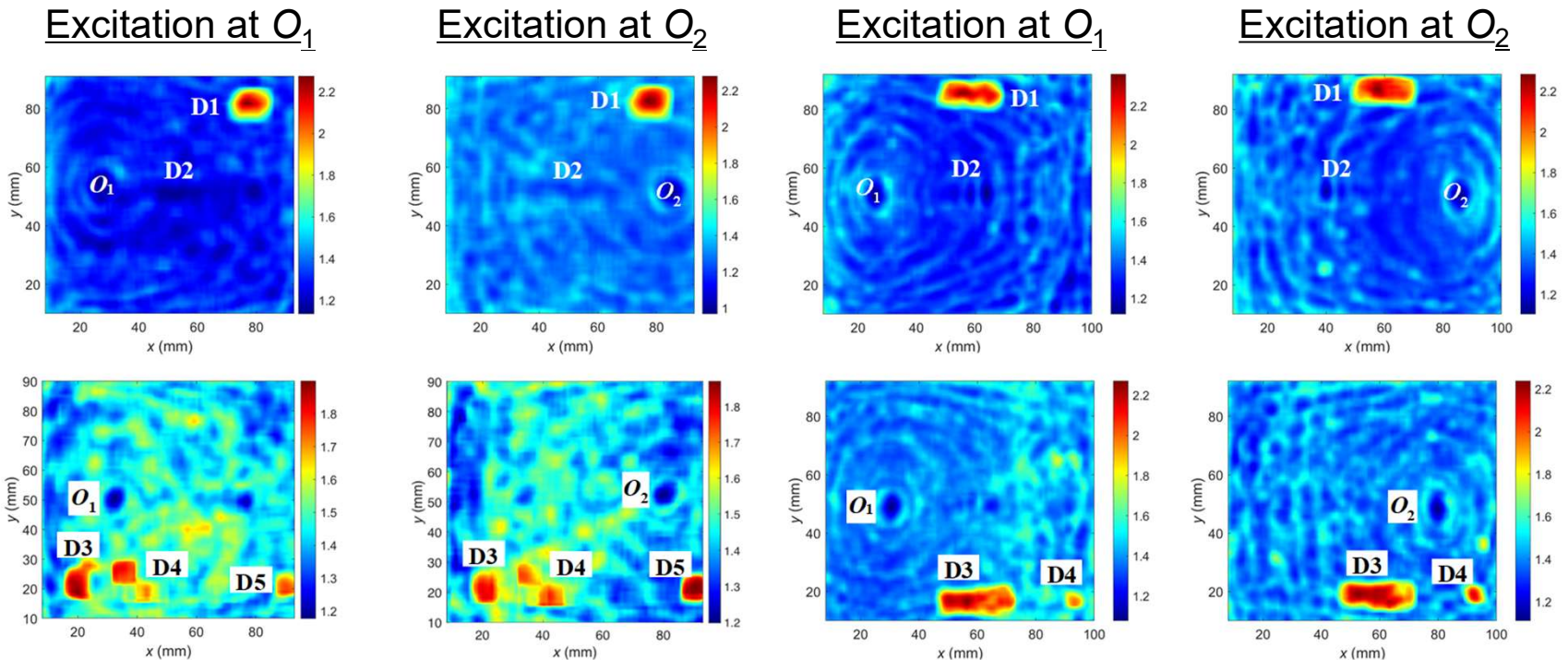
Imaging results on sample #2 and #3



Sample #2 ($R=20$ mm)

Sample #3 ($R=10$ mm)

Top surface



Bottom surface

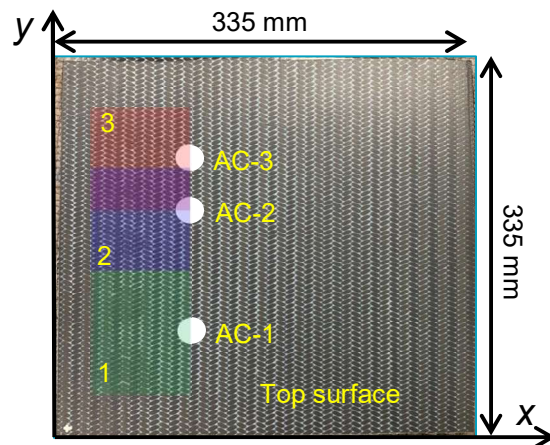
- ❑ Sample #2: Total 5 delamination in the plate, with D1 close to top surface, D3, D4 and D5 close to the bottom surface, and D2 likely in the middle plane
- ❑ Sample #3: Total 4 delamination in the plate, with D1 close to top surface, D3 and D4 close to the bottom surface, and D2 likely in the middle plane
- ❑ Overall, the delamination are visualized in all three plates including the one the smallest radius of curvature

Case 3: “pillow” defect evaluation



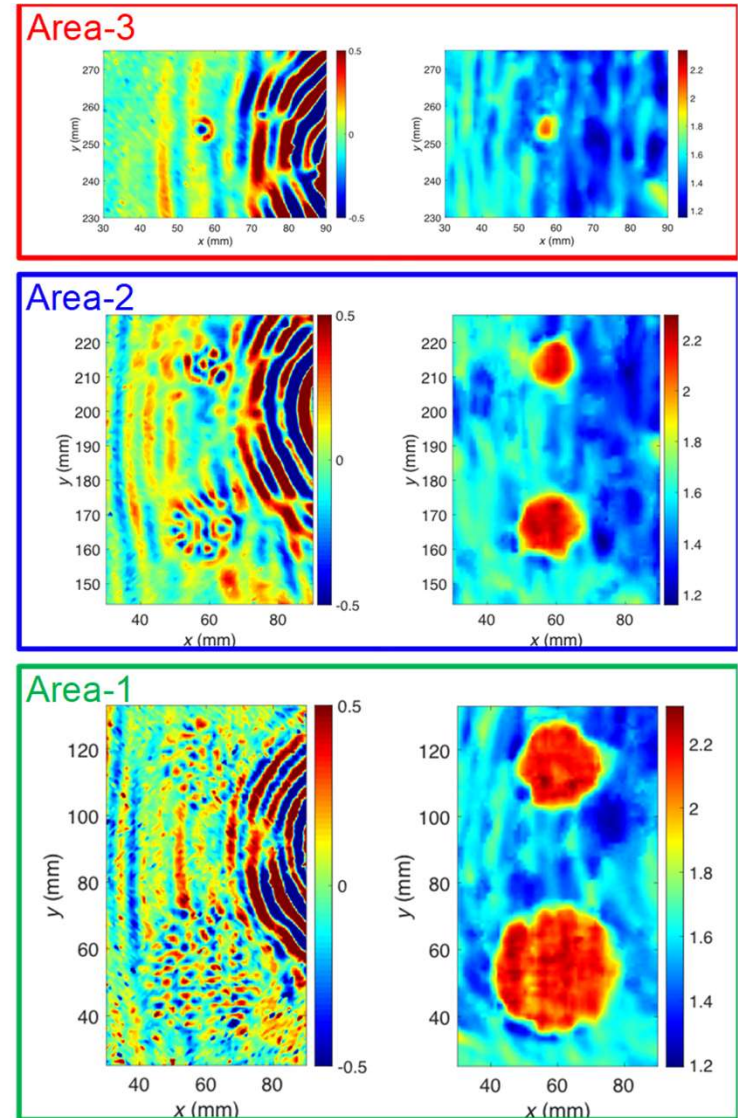
- ❑ Specimen: ~13.3 mm thick composite plate with unknown “pillow” defects
- ❑ Imaging methods: maximum intensity wavenumber imaging method
- ❑ Sensing: three area scans for each excitation on each surface

Actuation and sensing setup

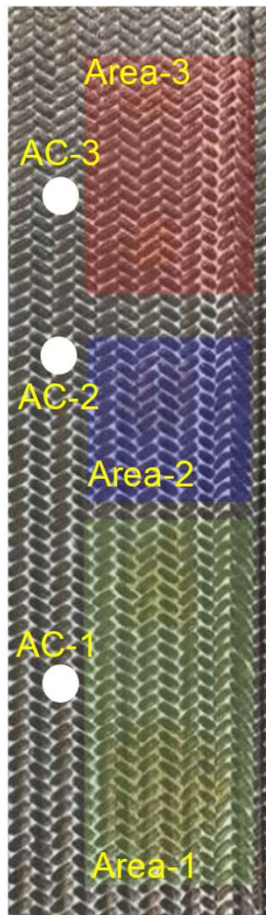


(Courtesy of NASA Langley Research Center and ACP members)

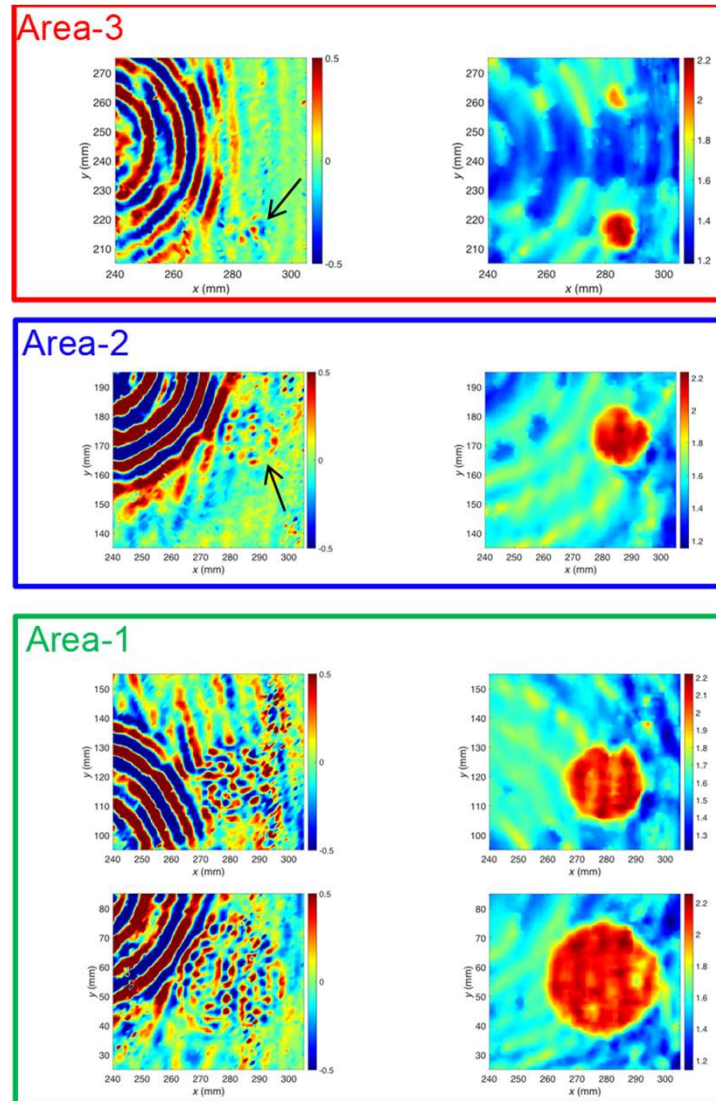
Results on the top surface



Results on the bottom surface



(Courtesy of NASA Langley Research Center and ACP members)

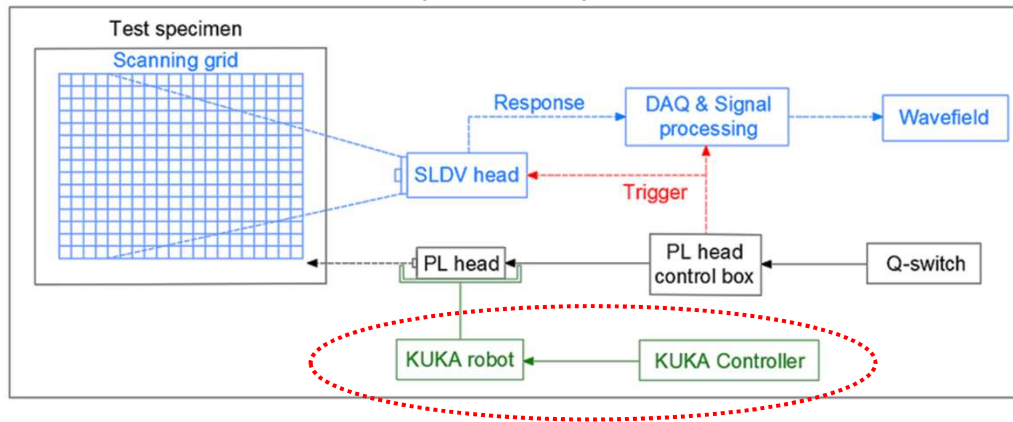


- ❑ 10 circular defects are detected with 5 of them close to the top surface and 5 close to the bottom surface
- ❑ The quantified diameters of the defects are 38 mm, 25 mm, 19 mm, 13 mm, and 6 mm respectively

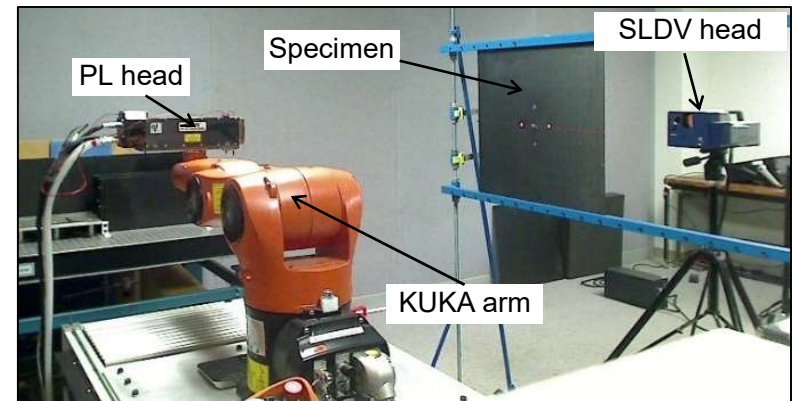
Automatic PL-SLDV system



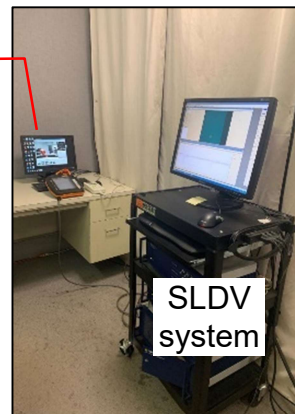
System layout



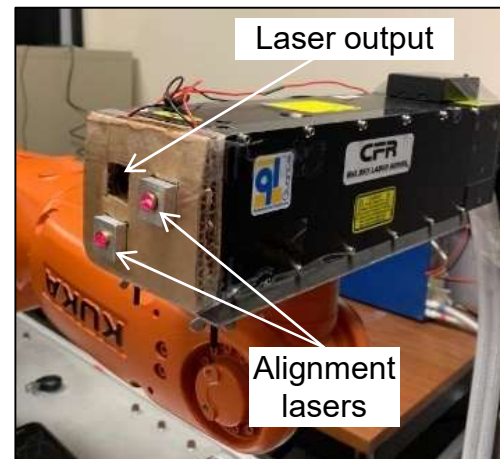
Experimental setup



Control system

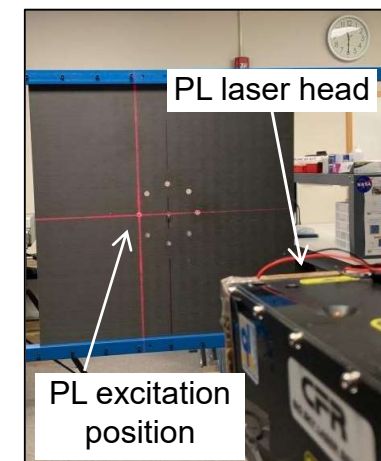


Alignment lasers



(Ma and Yu, 2020)

Alignment lasers locating the excitation points

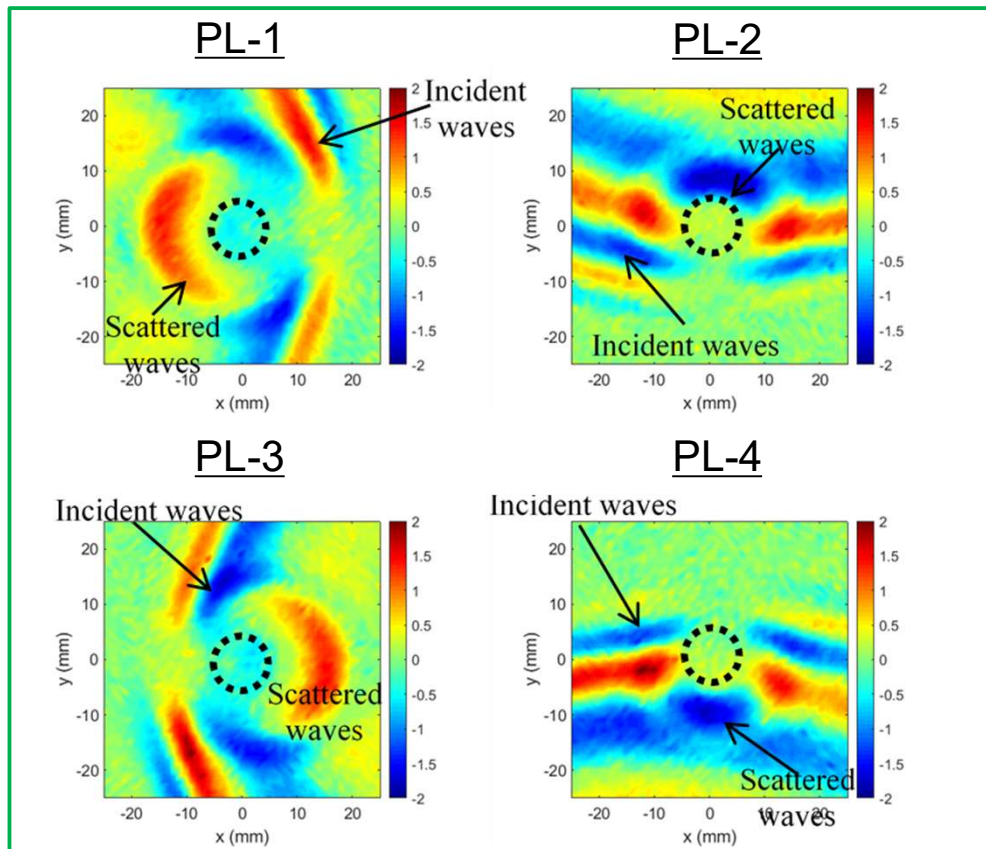
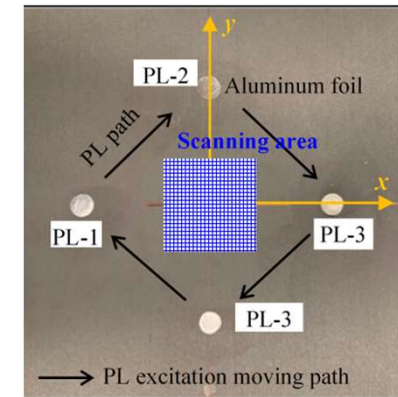


Evaluation on a composite plate

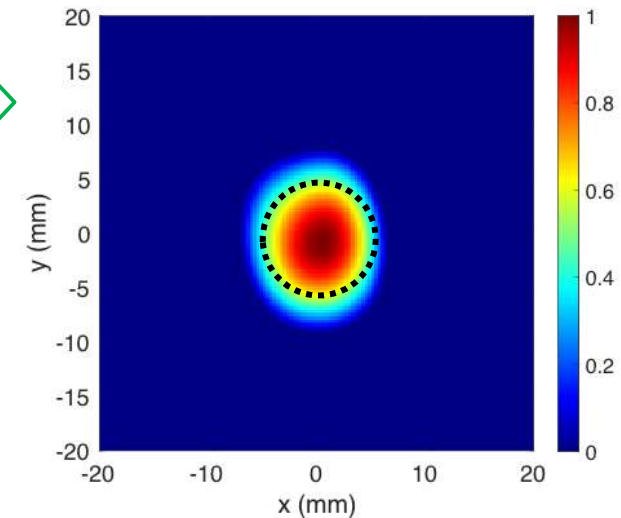


- ❑ Specimen: 2.54 mm thick plate 8-ply quasi-isotropic CFRP composite plate with layup $[0,45,90,-45]_s$
- ❑ Actuation: PL excitation at four locations PL-1, PL-2, PL-3, and PL-4 from four directions

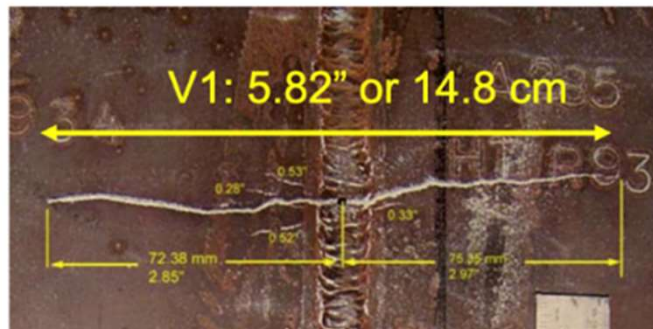
Actuation and sensing setup



Network imaging



Part II: Applications on aerospace and nuclear structures on nuclear structures

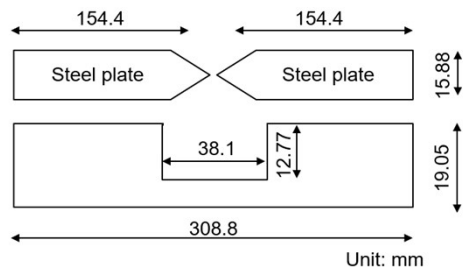


Case 1: stress corrosion cracking

Specimen

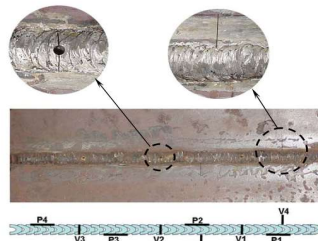
- ❑ Welded steel plate by joining two A285 carbon steel plates using GMAW procedure
- ❑ The specimen was not heat treated to relieve the residual stress after welding

Welding of steel plates

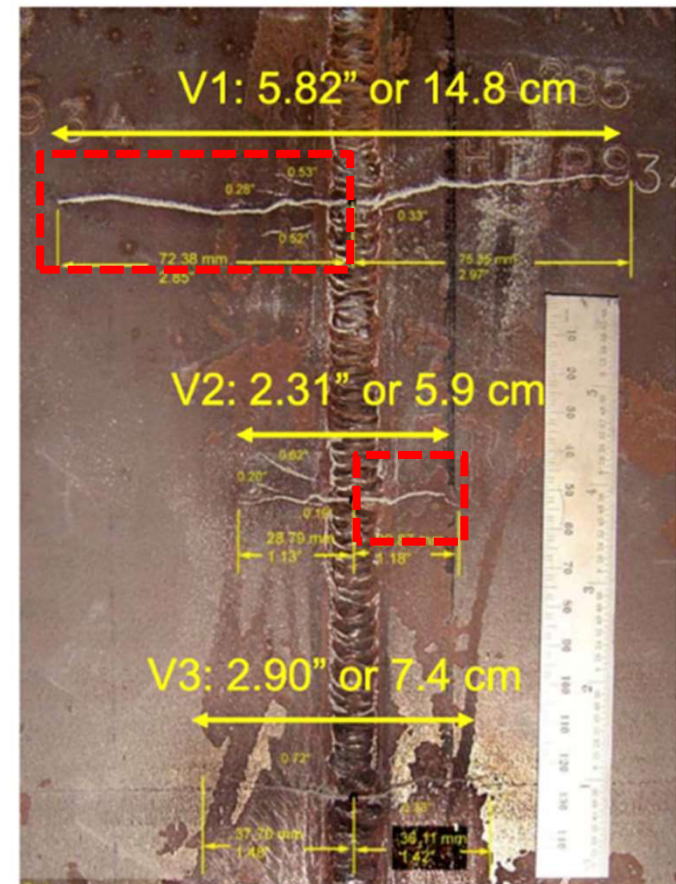


(Lam et al., 2005)

Starter cracks

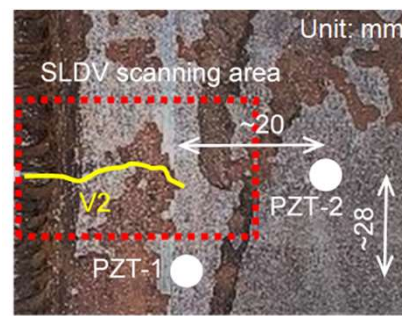
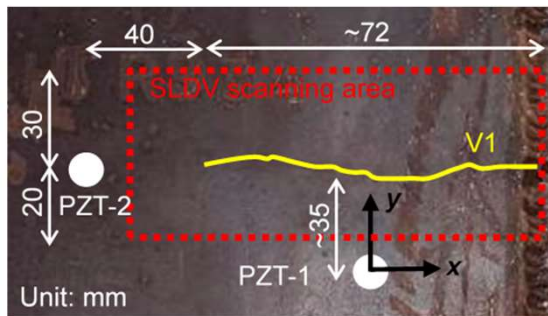


SCC inspected by magnetic particle test



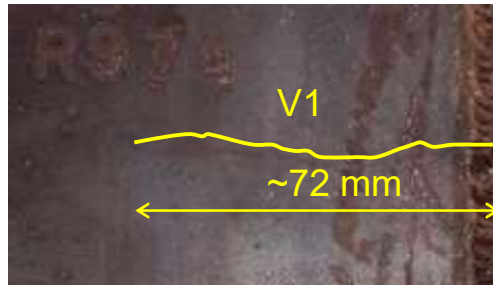
(Lam et al., 2005)

Actuation and sensing setup using PZT-SLDV system

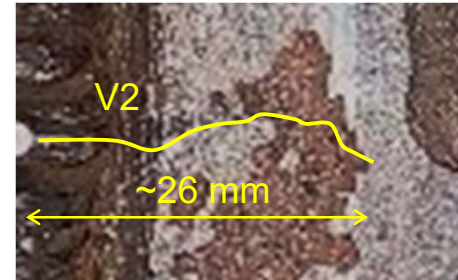


Filtering reconstruction imaging results

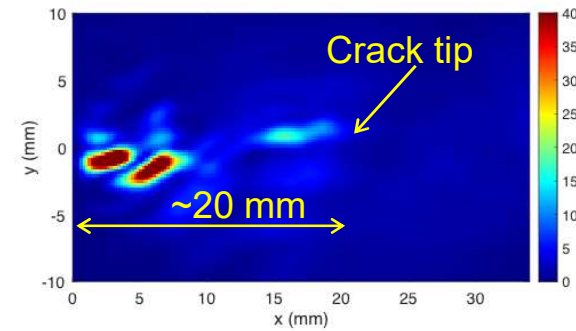
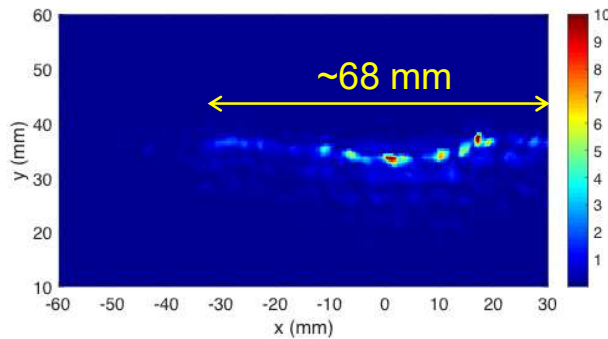
V1 imaging results



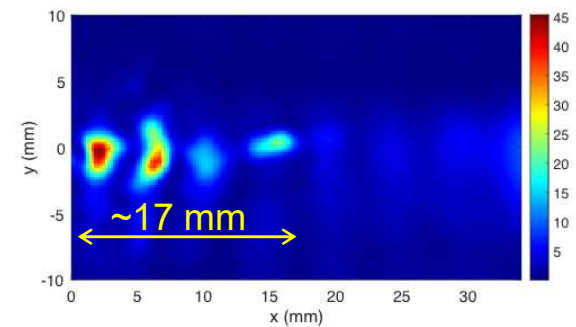
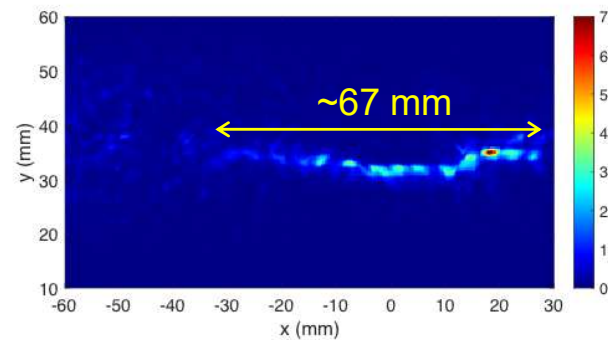
V2 imaging results



Normal inspection

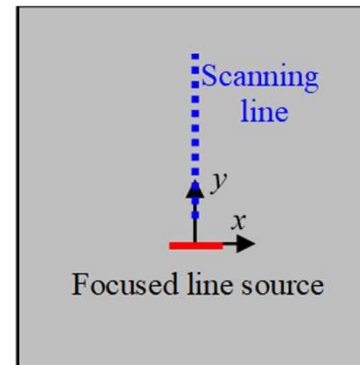
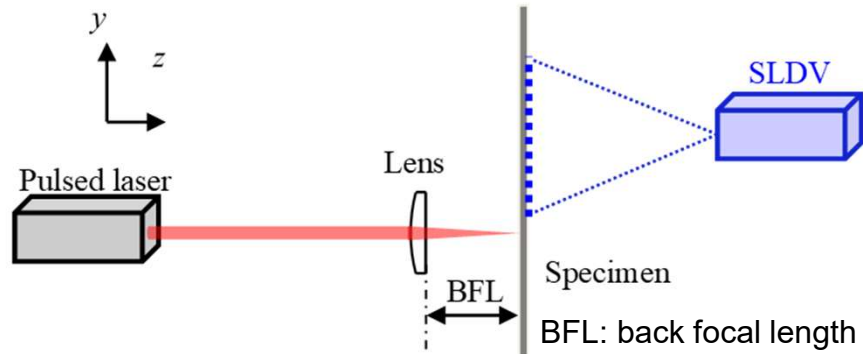


Parallel inspection



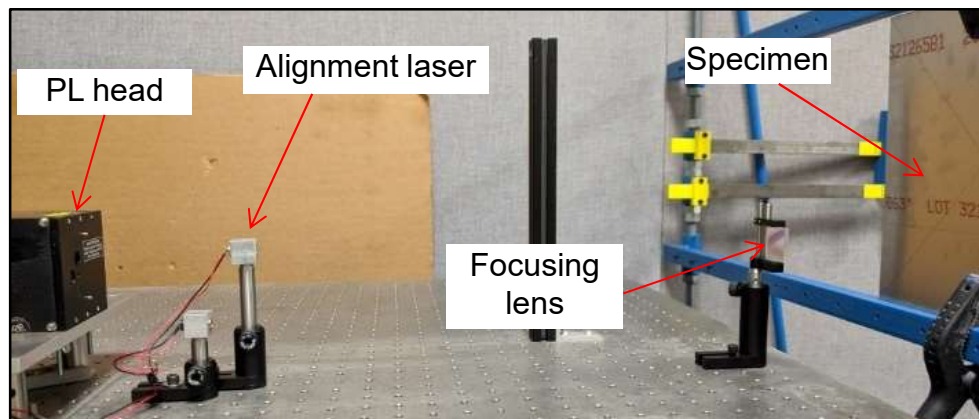
Case 2: material characterization on metallic plates

Focused PL-SLDV system setup

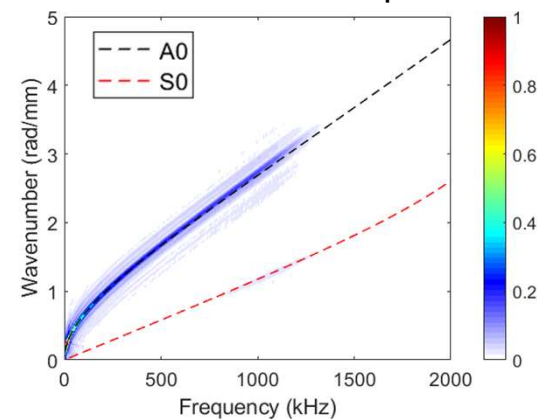


- Actuation: focused PL line source (10 mJ energy) with ~0.2 mm width and 7 mm length
- Sensing: line scan

PL-lens-specimen schematic



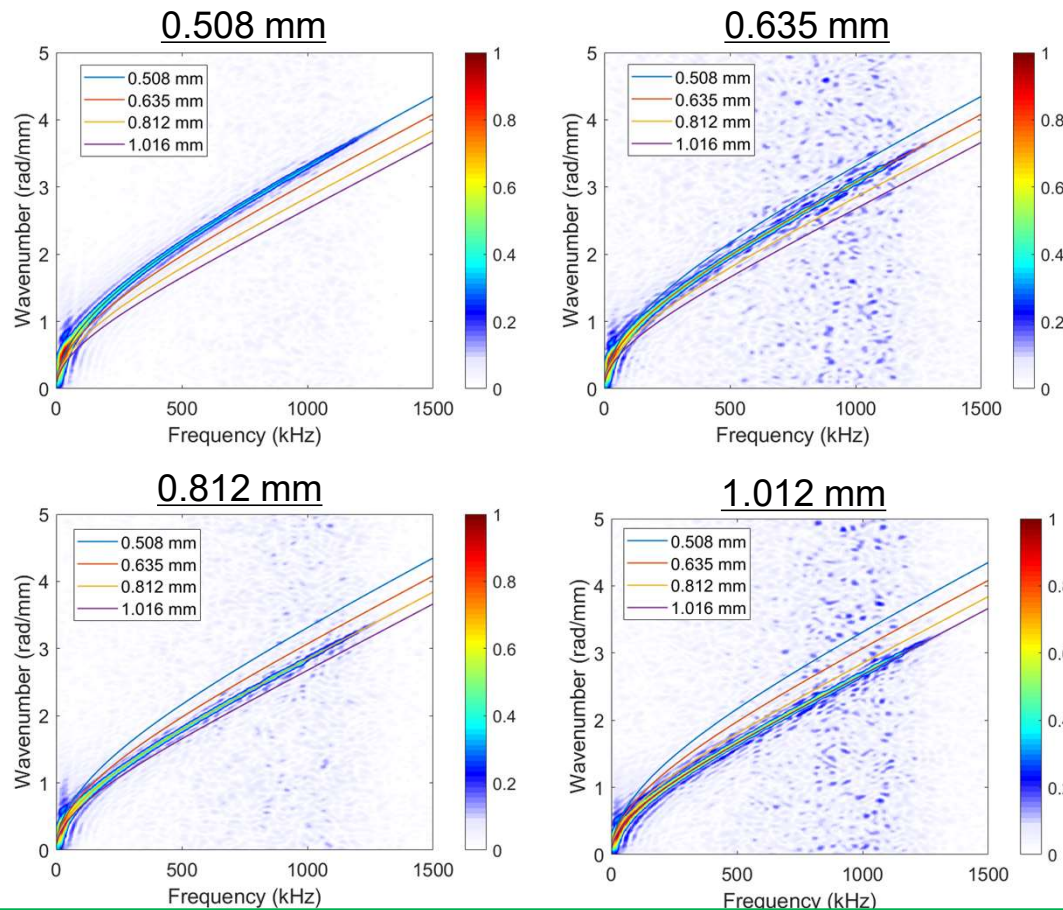
f-k spectrum on an aluminum 2024-T3 plate



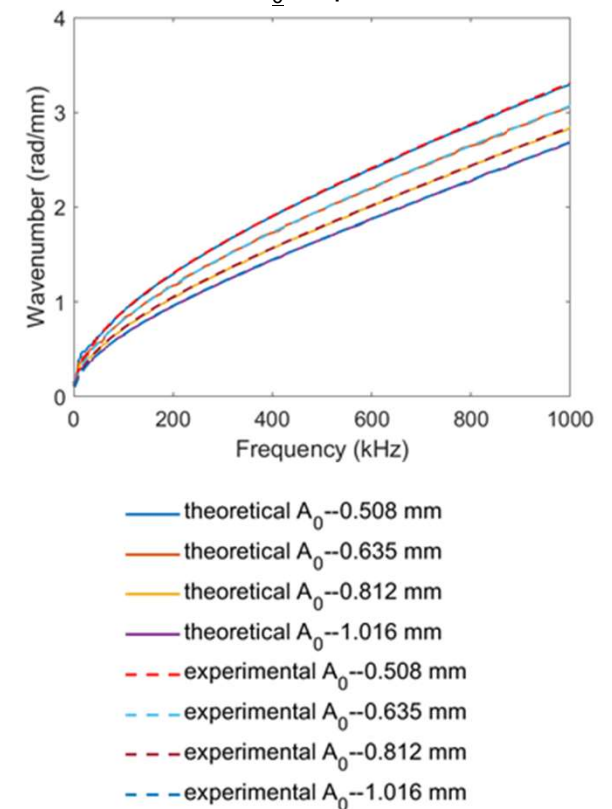
Thickness estimation

- Specimen: four aluminum 2024-T3 plates with 0.508 mm, 0.635 mm, 0.810 mm and 1.016 mm thickness

f-k spectra results



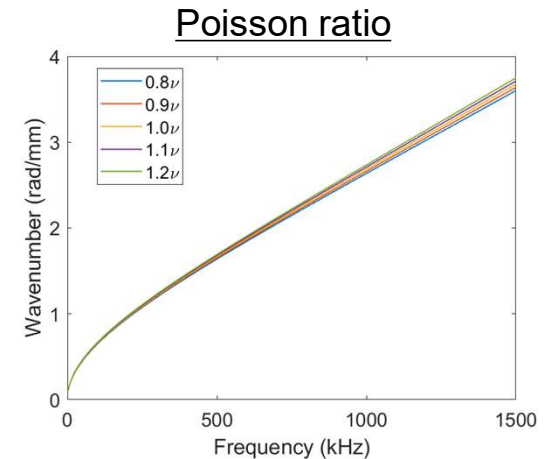
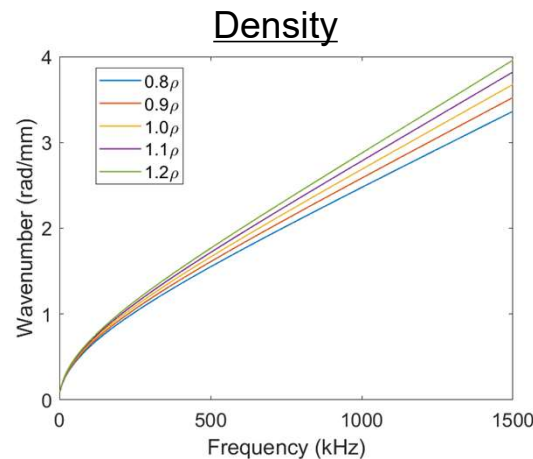
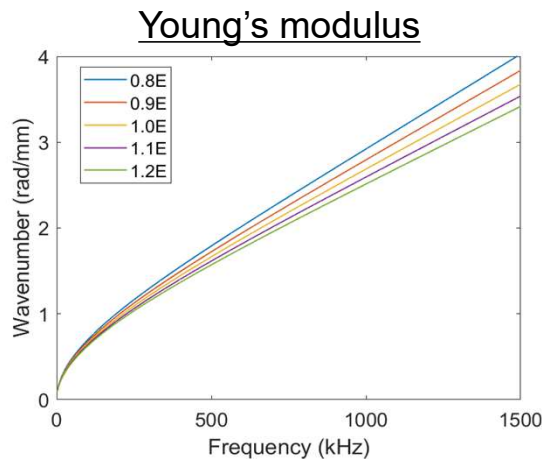
Comparison between experimental and theoretical A_0 dispersion curve



Theoretical parametric study

- Dispersion curve sensitivity to Young's modulus (E), density (ρ) and Poisson ratio (ν)
 - 20%, -10%, 0, +10%, +20%

Material	Aluminum 2024-T3
Young's modulus (GPa)	73.1
Poisson ratio	0.33
Density (kg/m ³)	2780



Wavenumber change at 500 kHz
with different Young's modulus

ΔE (%)	k (rad/mm)	Δk (%)
-20	1.790	+7.5
-10	1.723	+3.5
0	1.665	0
+10	1.615	-3.0
+20	1.571	-5.6

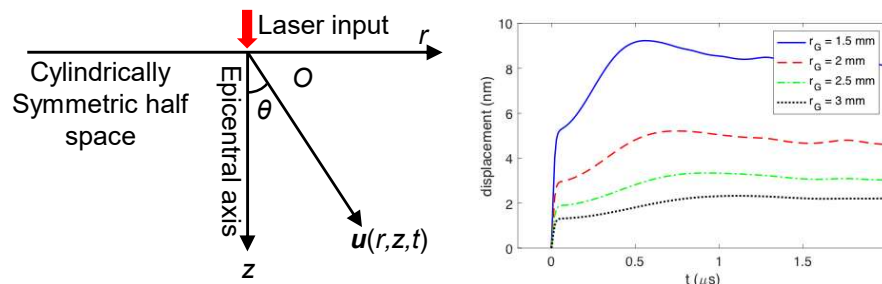
Wavenumber change at 500 kHz
with different densities

$\Delta \rho$ (%)	k (rad/mm)	Δk (%)
-20	1.550	-6.9
-10	1.610	-3.3
0	1.665	0
+10	1.717	+3.1
+20	1.767	+6.1

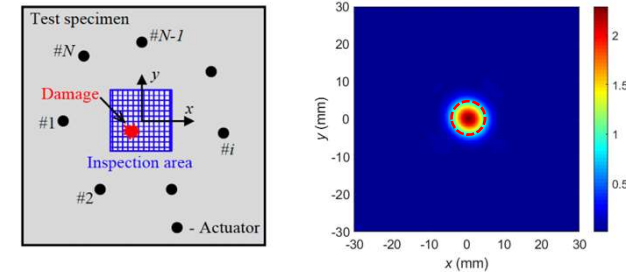
Conclusions: Part I

- ❑ An actuator network Lamb wave imaging algorithm that can quantify damage with complex profiles is developed
 - Can provide multidimensional wavefield data from different perspective
 - Can quantify great details of complex damage
- ❑ A noncontact/remote PL-SLDV NDE system is developed and evaluated for damage inspection on both metallic and composite plates
 - Can excite and measure Lamb waves in noncontact and remote manner
 - Is reliable for damage detection and evaluation on both metallic and composite structures
- ❑ Thermoelastic modeling of pulsed laser actuation on isotropic half space structures is derived and numerical and experimental parametric study is performed
 - Reducing the laser beam radius will increase the epicenter displacement
 - Increasing the excitation energy will increase the epicenter displacement

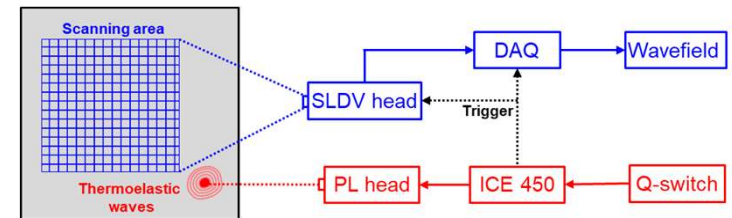
Pulsed laser actuation model and resulted energy effect



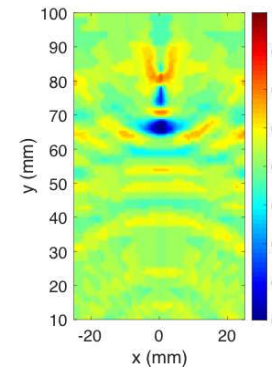
Actuator network setup and proof of concept imaging results



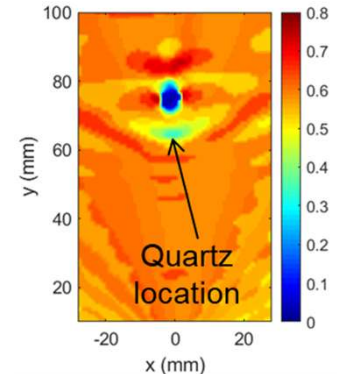
Noncontact/remote PL-SLDV system



Imaging results on an aluminum plate



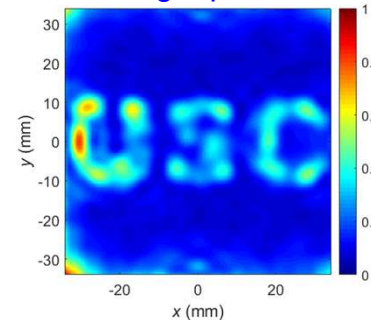
Imaging results on a composite plate



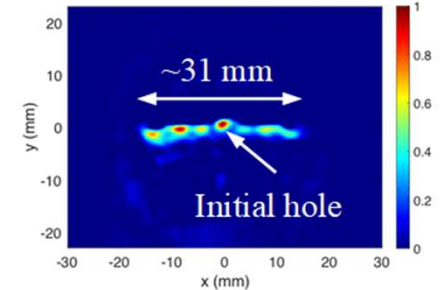
Conclusions: Part II

- ❑ The developed NDE/SHM systems and methodology are applied on aerospace and nuclear structures, the suitable experimental setup and imaging methods within each case for reliable damage detection purpose are demonstrated
 - Complex damage in aluminum plates: Full 2D profile is quantified with great details
 - Fatigue crack in aluminum plates: both initial hole and length quantified
 - Various composite defects: all detected with effective imaging methods
 - Stress corrosion cracking: all detected with length quantified
 - Material characterization: plate thickness estimated, dispersion curve sensitivity study is performed

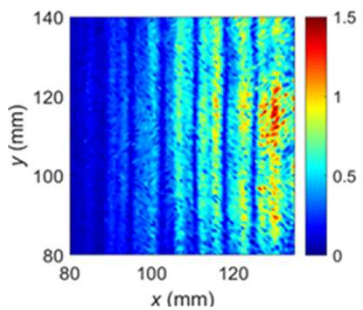
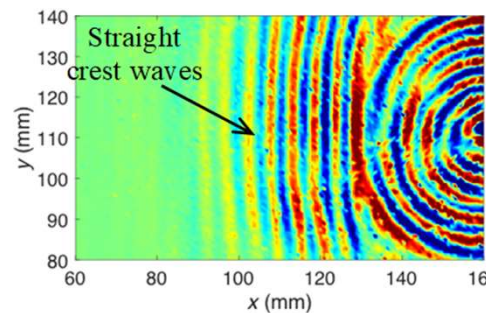
Complex letter cluster damage quantified



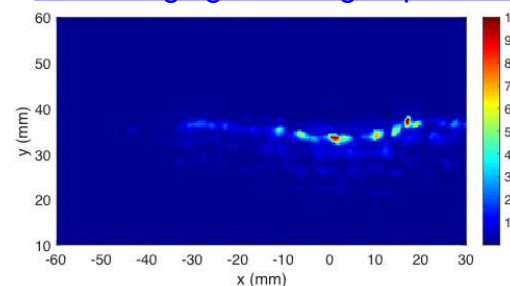
Imaging of fatigue crack with initial hole and length quantified



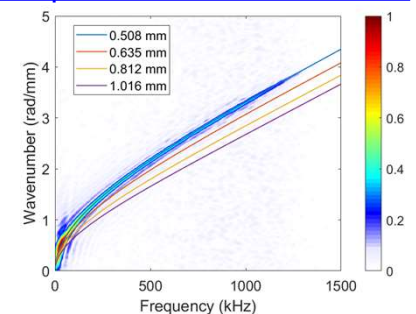
Wavefield defect visualized



SCC imaging with length quantified



Thin plate thickness estimated



Major contributions

- ❑ A high-resolution actuator network imaging method with demonstrated capabilities of imaging damage with complex profiles with great details
- ❑ A reliable noncontact/remote laser based Lamb wave NDE system accompanied with effective evaluation methods for both damage detection and material characterization purpose
- ❑ Modeling and parametric study on the pulsed laser actuation on isotropic half space structures
- ❑ Systematic study of Lamb wave based NDE reliability and effectiveness on various real-world applications including typical damage and defects

Future work

- ❑ Further study and investigation of the actuator network imaging method is recommended, including investigating different schematics of actuator number and arrangement, trying out other image fusion techniques, and performing inspection frequency study .
- ❑ Analytical study and/or FEM modeling of laser excited Lamb waves as well as the excitation mechanism is recommended for investigation in order to set up better experimental parameters for laser based NDE.
- ❑ Investigation of the Laser based NDE method sensitivity for material characterization as well as extending to multi-layer structures are recommended.

Journal publications

- 5 Yu, L.; and **Ma, Z.** (2020) “Various types of defects detection in flat and curved laminated composite plates using nonintrusive Lamb wave system,” *ASME Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems* (under review)
- 4 Tian, Z.; **Ma, Z.**; Xiao, W.; and Yu, L. (2020) “Noncontact laser vibrometry based fence-like arrays with wavefield filtering assisted adaptive imaging algorithms for detecting multiple pits in a compact cluster,” *Structural Health Monitoring* (in revision)
- 3 Tian, Z.; Xiao, W.; **Ma, Z.**; and Yu, L. (2020) “Visualization and quantification of corrosion damage in metal plates: Part I. Lamb waves wavefield analysis for corrosion profiling,” *Mechanical Systems and Signal Processing* (in revision)
- 2 **Ma, Z.**; and Yu, L. (2020) “Lamb wave imaging with actuator network for damage quantification in aluminum plate structures,” *Journal of Intelligent Material Systems and Structures*, p.1045389X20952536.
- 1 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.

☐ In preparation

- 2 **Ma, Z.**; and Yu, L. (2020) “Stress corrosion cracking in welded steel and nondestructive evaluation using guided ultrasonic waves”
- 1 **Ma, Z.**; and Yu, L. (2020) “Noncontact crack imaging and evaluation through laser generated wideband Lamb waves”

Conference and other Publications

☐ Conference papers

- 6 Xiao, W.; **Ma, Z.**; and Yu, L. (2020), “Nondestructive Material Thickness Evaluation by Lamb Waves,” 2020 American Nuclear Society (ANS) Virtual Winter Meeting, paper # 2020-33416 (accepted)
- 5 **Ma, Z.**; and Yu, L. (2020 Sept) “Noncontact/remote material characterization using ultrasonic guided wave methods”, *Proceedings of the ASME 2020 Smart Materials, Adaptive Structures and Intelligent Systems*, Virtual Conference, 15 September 2020, paper # 2020-2288 (accepted)
- 4 **Ma, Z.**; and Yu, L. (2020 Aug) “Ultrasonic nondestructive evaluation of stress corrosion crack in welded steel plate”, *Proceedings of the ASME 2020 Pressure Vessels & Piping, Virtual Conference*, 3 August 2020, paper # 2020-21794 (accepted)
- 3 **Ma, Z.**; and Yu, L. (2020 April) “Ultrasonic Lamb wave inspection of composite defects,” In *Health Monitoring of Structural and Biological Systems XIV*, Vol. 11381, p. 1138103, International Society for Optics and Photonics, 2020.
- 2 **Ma, Z.**; and Yu, L. (2020 April) “Laser based remote and rapid inspection for composite plates.” In *Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems*, Vol. 11382, p. 113820H, International Society for Optics and Photonics, 2020.
- 1 **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, 2020.

☐ Poster presentation

- 1 **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.

☐ US patent

- 1 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 (pending)

Thank you!

