Phased Array Beamforming and Imaging in Composite Laminates Using Guided Waves

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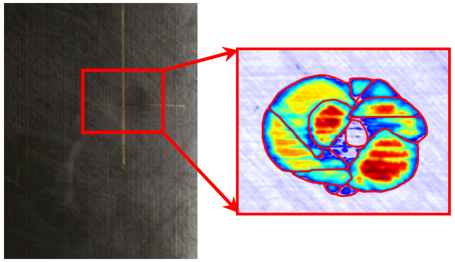
Outline

- Background and overview
- Beamforming in anisotropic composite laminates
  - *Generic beamforming formula*
  - *Array characterization*
- Phased array implementation
  - *Piezoelectric transducer (PZT)-scanning laser Doppler vibrometer (SLDV) sensing system*
- Proof of concept experiment
  - *Detection of multiple defects in anisotropic composite plate*
- Conclusions

Research Background and Motivation

- Rapid damage inspection in composites
  - Increased use of composites in aerospace vehicles (space and aeronautics)
  - Composites have unique damage types (compared to metallic plates), such as microcracking and delamination
  - Rapid inspection techniques for detecting and quantifying damage in large composites
    - ✓ Critical for ensuring operability and safety of composite structures
    - ✓ Imperative for evaluating and certifying the materials, in the development and manufacturing of next-generation composite materials

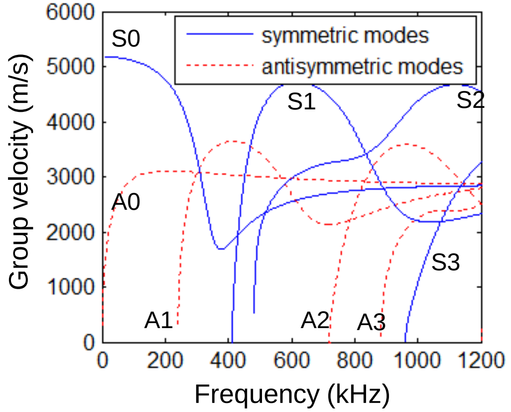
Composite crew module
Image from www.nasa.gov



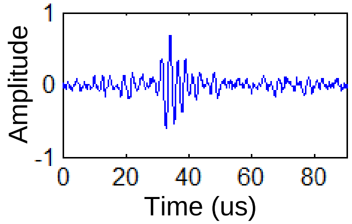
C-scan image of a hidden delamination in a composite plate

Guided Ultrasonic Wave Damage Detection

- **Guided wave damage detection**
  - Sensitivity to a variety of damage types
  - Traveling a relatively long distance with low energy loss
  - Promising detection results on metallic plates

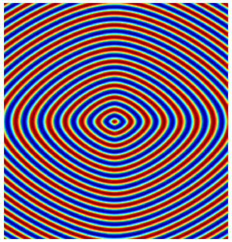


- **Challenges**
  - Dispersive and multi-modal
  - Guided wave signal: incident, reflection and noise
  - Complex wave propagation in anisotropic composite plates
  - Additional data analysis is needed for damage diagnosis



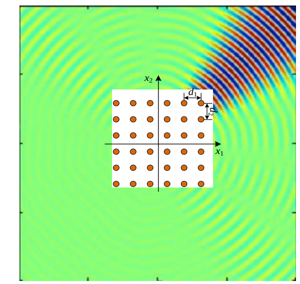
A waveform under a narrowband excitation indeed containing (1) an incident A0 wave, (2) a reflected A0 wave, and (3) noise

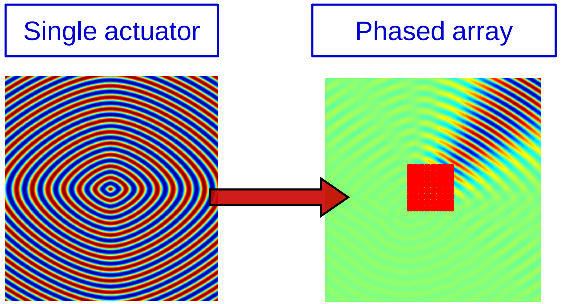
Directionally dependent wave propagation



Research Overview

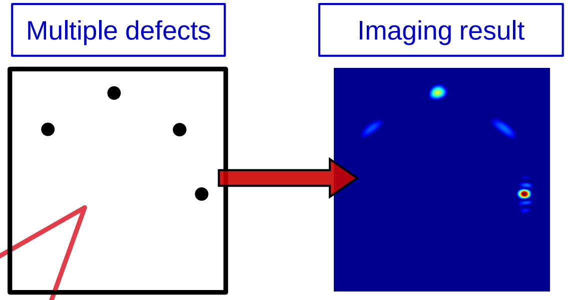
- State of the art—guided wave phased arrays
  - A small number of sensors placed close to each other in a compact format
  - Steering of the array output in any desired direction through phase/time delays
  - Perform a sweep inspection of the entire structure in a way analogous to radar
  - Phased arrays in isotropic plates: Wilcox et al. 2005, Yu and Giurgiutiu 2008; Stepinski 2007; Fromme et al. 2006; Purekar et al. 2004; Kwon et al. 2013
  - Phased arrays in anisotropic composites: Yan and Rose 2007; Rajagopalan et al. 2006; Purekar and Pines 2010; Leleux et al. 2013; Osterc et al. 2013





- Objectives
  - Phased array beamforming in anisotropic composites
  - Rapid damage detection in anisotropic composites

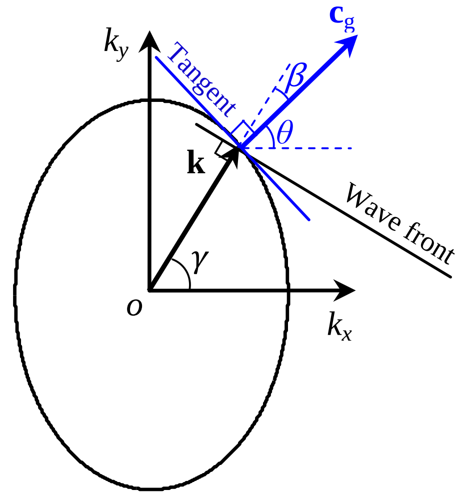
- Our work
  - Generic beamforming formula for anisotropic composites
  - Phased array implementation using PZT-SLDV system
  - Detection of multiple defects in a CFRP plate



Can we multiple defects in an anisotropic composite plate ?

Beamforming in Anisotropic Composite Laminates

- Assumptions: far-field, uniform point source
- Based on the traditional delay and sum beamforming
- Unique of this method
  - ✓ *Phase delay in frequency domain*
  - ✓ *Directionally dependent wavenumber and phase velocity are considered*
  - ✓ *The energy skew angle β between wavenumber vector* ***k*** *and group velocity vector* $\mathbf{c}_g$ *is considered*



Point source at the origin

$$u(t,\mathbf{x}) = Ae^{j(\omega t - \mathbf{k}\cdot\mathbf{x})}$$

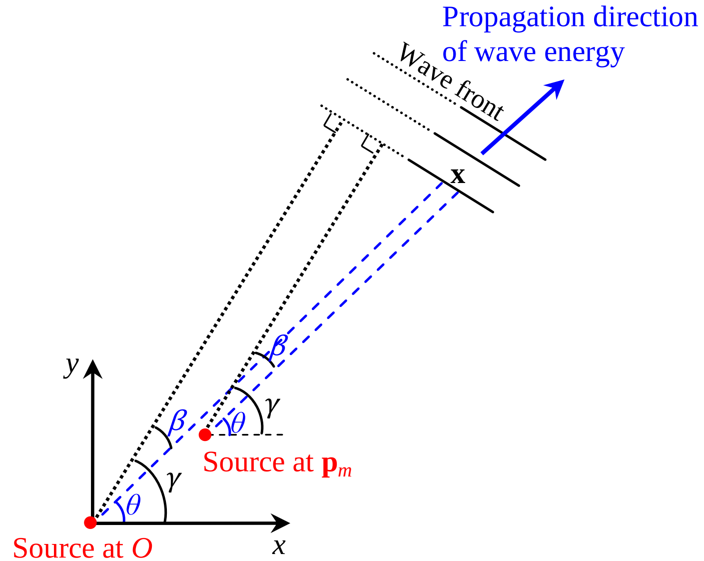
m^{th} element at $\{\mathbf{p}_m\}$

$$u(t,\mathbf{x}) = Ae^{j[\omega t - \mathbf{k}\cdot(\mathbf{x}-\mathbf{p}_m)]}$$

Delay and sum beamforming

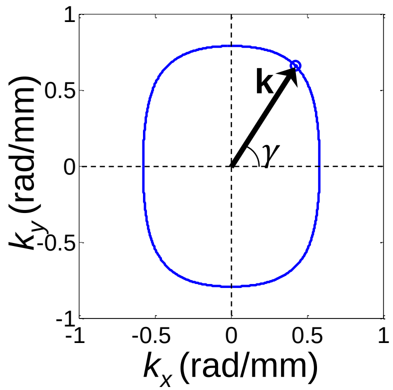
$$z(t,\mathbf{x}) = u(t,\mathbf{x})\sum_{m=0}^{M-1} w_m e^{j[\mathbf{k}\cdot\mathbf{p}_m - \Delta_m(\theta_S)]}$$

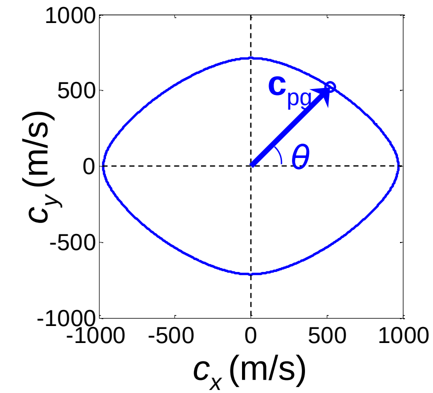
Delay $\Delta_m(\theta_S) = \mathbf{k}(\omega, \theta_S + \beta_S)\cdot\mathbf{p}_m$



Beamforming in an Anisotropic $[0_2/90_2]_s$ CFRP Plate

- Test plate: 0.85 mm thick 8-ply CFRP plate with $[0_2/90_2]_s$ layup
- Wave mode: A_0 mode at 90 kHz
- Wavelength: 11 mm $\geq \lambda_{y,min} \geq$ 8.0 mm
- Array configuration: 16 $\times$ 16 grid array
- Element spacing: $d_x = d_y$ = 2 mm



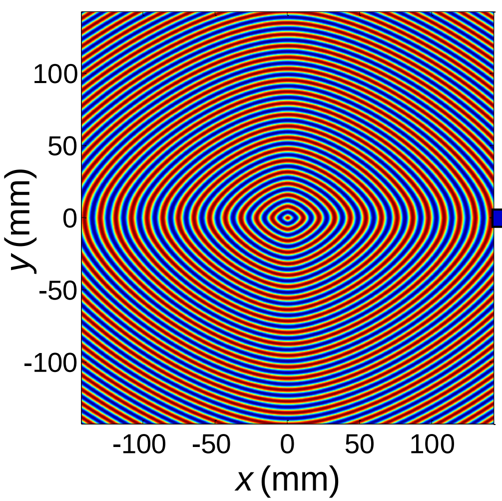


Point source at the origin

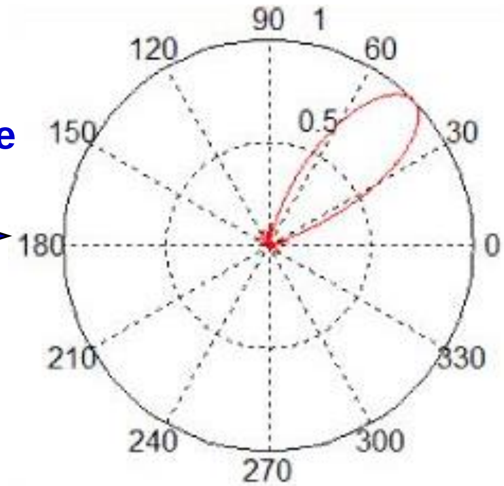
$$u(t,\mathbf{x}) = Ae^{j(\omega t - \mathbf{k}\cdot\mathbf{x})}$$

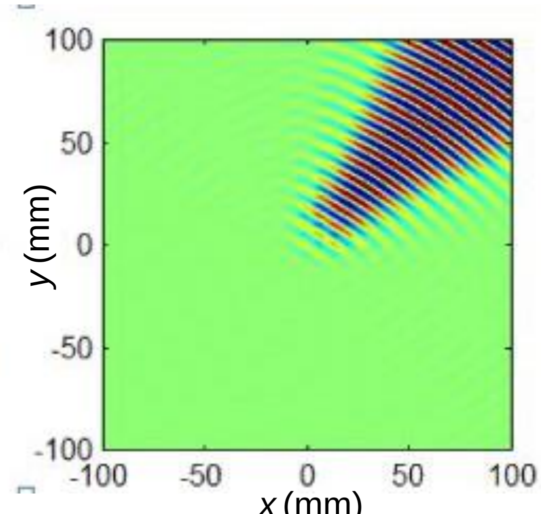
Array beamforming

$$z(t,\mathbf{x}) = u(t,\mathbf{x})\sum_{m=0}^{M-1} w_m e^{j\left[\mathbf{k}\cdot\mathbf{p}_m - \Delta_m(\theta_S)\right]}$$

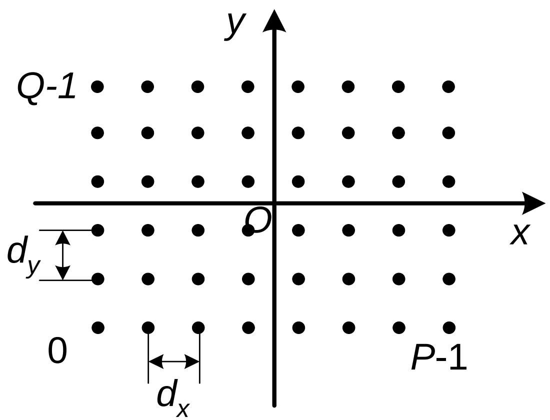


Beamforming Adjusting phase delay $\Delta_m(\theta_S)$

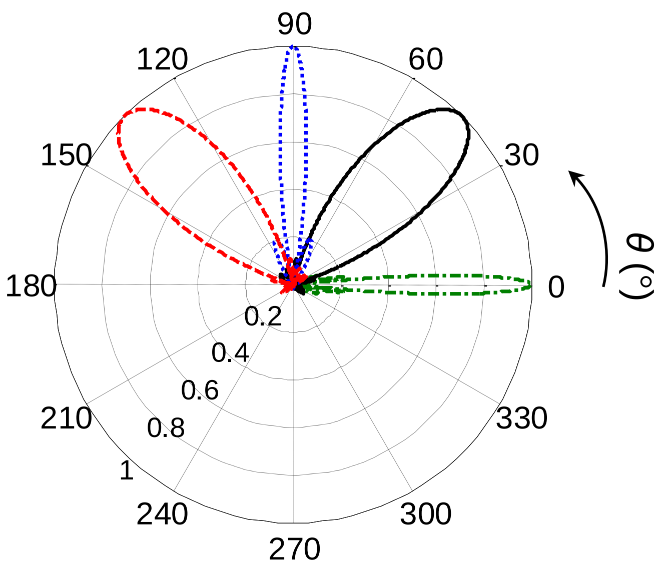


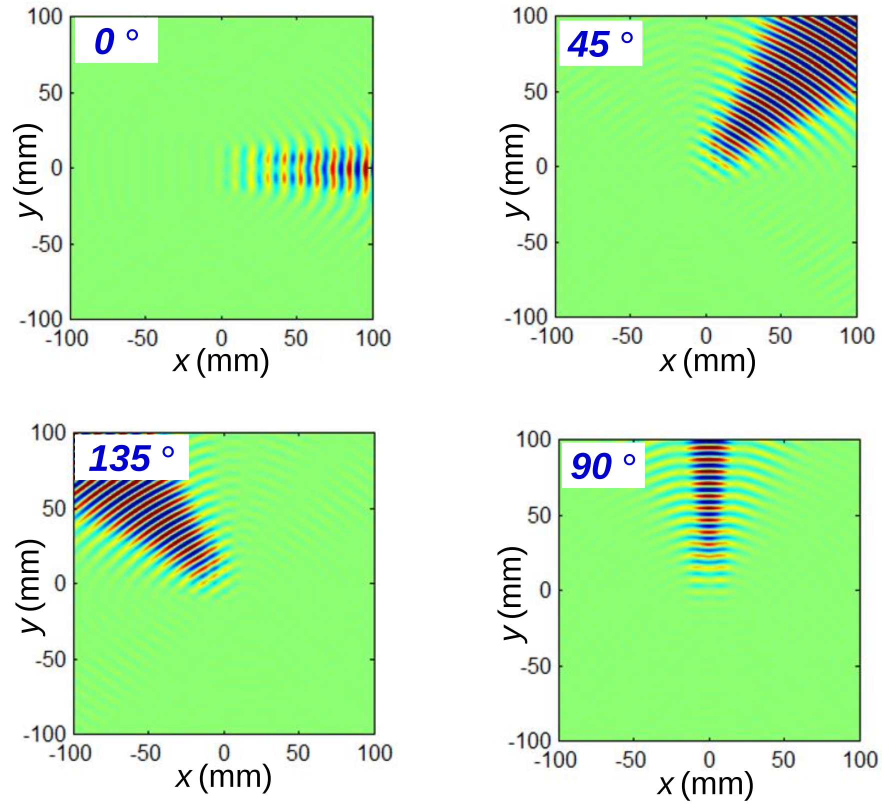


Beamforming Factor for Array Characterization



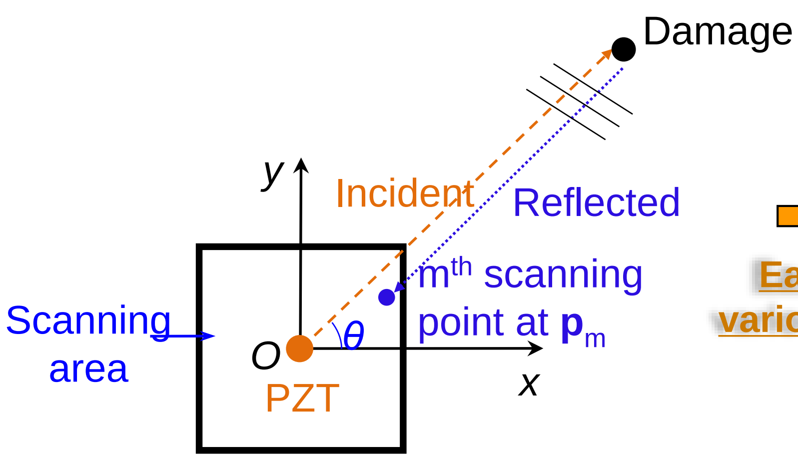
$$BF(\theta\,|\,w_{p,q},\theta_S)$$
$$=\frac{1}{PQ}\sum_{p=0}^{P-1}\sum_{q=0}^{Q-1}w_{p,q}e^{j[\mathbf{k}(\omega,\theta+\beta)-\mathbf{k}(\omega,\theta_S+\beta_S)]\cdot\left((p-\frac{P-1}{2})d_x,(q-\frac{Q-1}{2})d_y\right)}$$



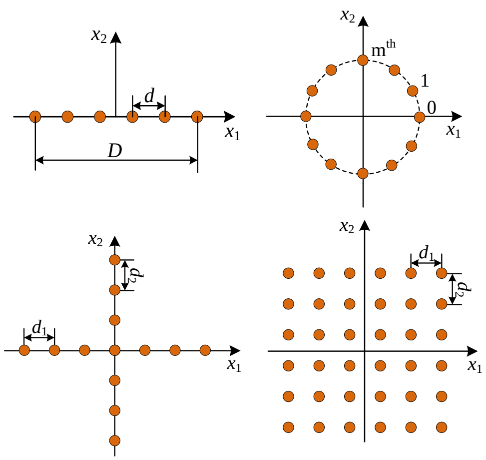


Phased Array Implementation using PZT-SLDV System

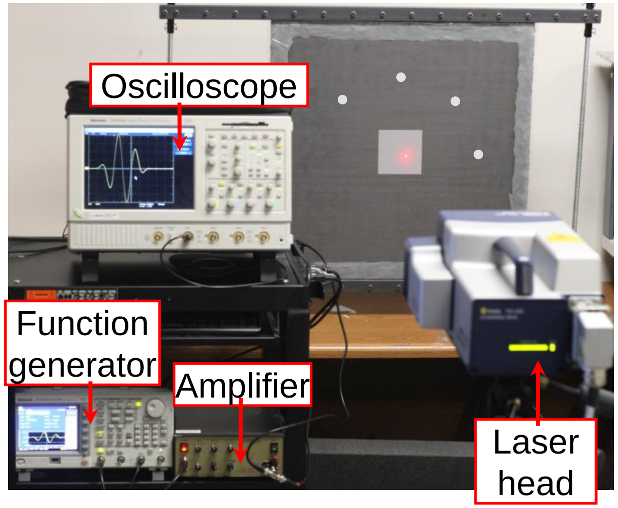
- PZT: to generate guided waves
- Scanning laser Doppler vibrometer (SLDV):
  Scan points are selected from the entire scan area to construct the array
- Higher spatial density and resolution (less than 0.1 mm)
- The scan points can be easily configured in different distribution
  - ✓ *Such as linear array, circular array, square array,*
  - ✓ *For different purposes such as parametric studies and array optimization*

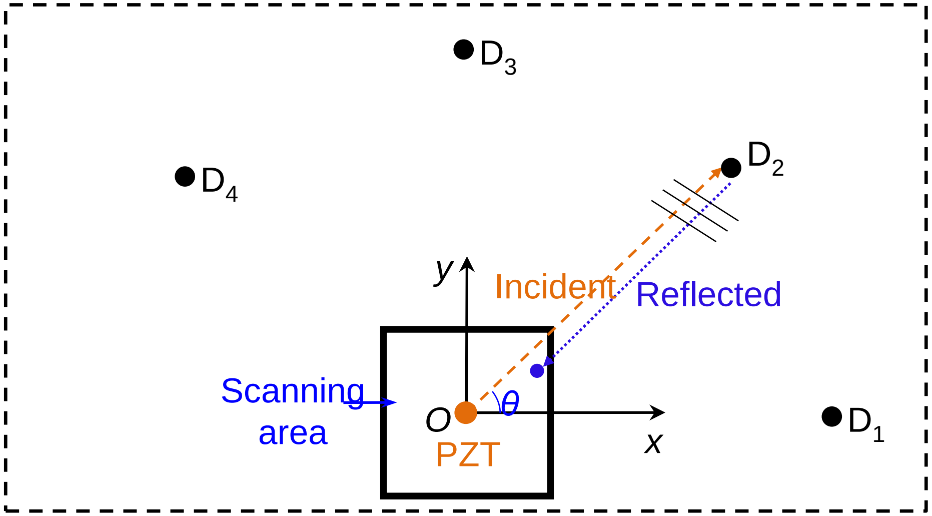


Easily configured into various array distributions



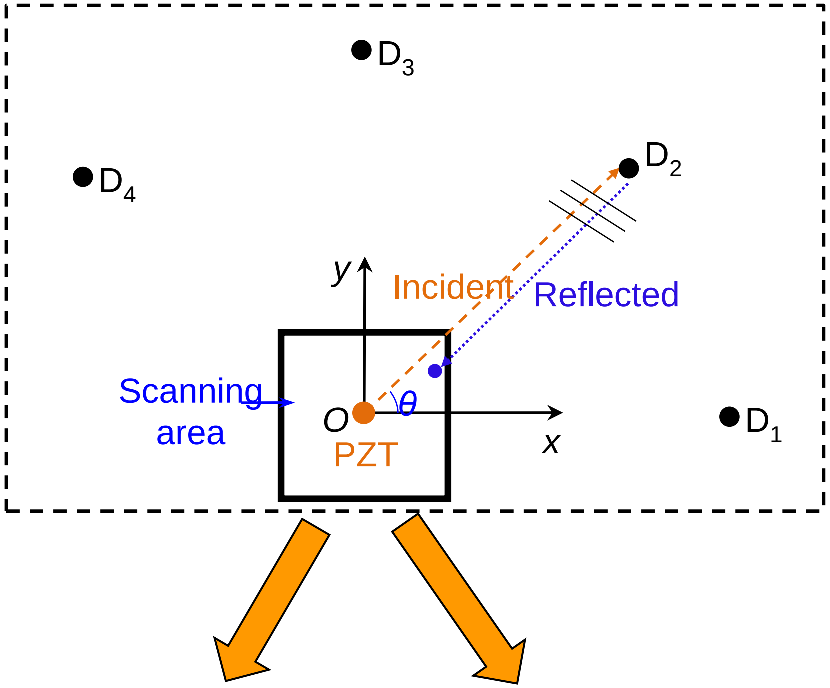
Detection of Multiple Defects in a CFRP Plate (Setup)





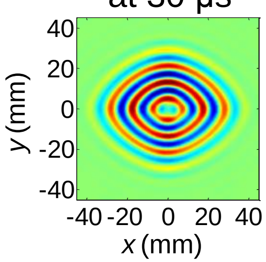
- Test plate: 0.85 mm thick 8-ply CFRP plate with $[0_2/90_2]_s$ layup
- Defects: four quartz rods (D_1, D_2, D_3 and D_4) bonded on the plate
  - Same distance 100 mm away from the array center
  - Different angles 0° , 45° , 90° and 135°
- PZT to generate guided waves
  - Excitation: 3-count tone burst at 90 kHz
- SLDV to measure wavefield in the scanning area
  - Dimensions: 45 mm × 45 mm
  - Resolution: 0.1 mm

Detection in a CFRP Plate

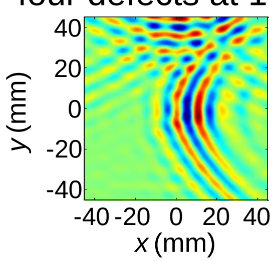


Guided waves measured in the scanning area

Incident waves at 30 μs



Reflected waves from the four defects at 140 μs



SLDV points at selected locations $\{\mathbf{p}_m\}$

Signal at each array point

↓

Delay and sum in frequency domain

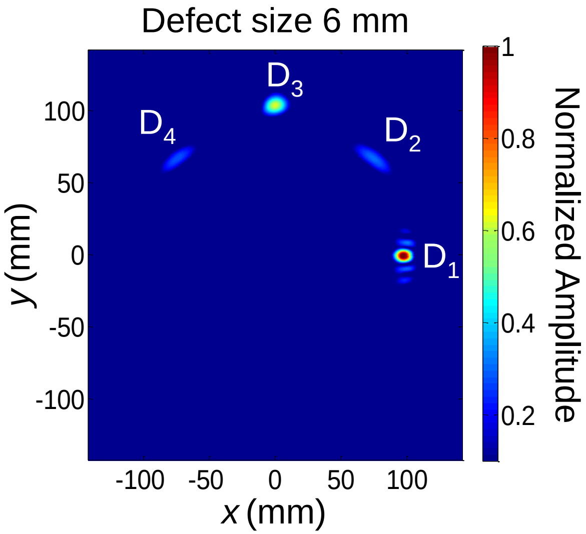
Frequency-space representation

↓

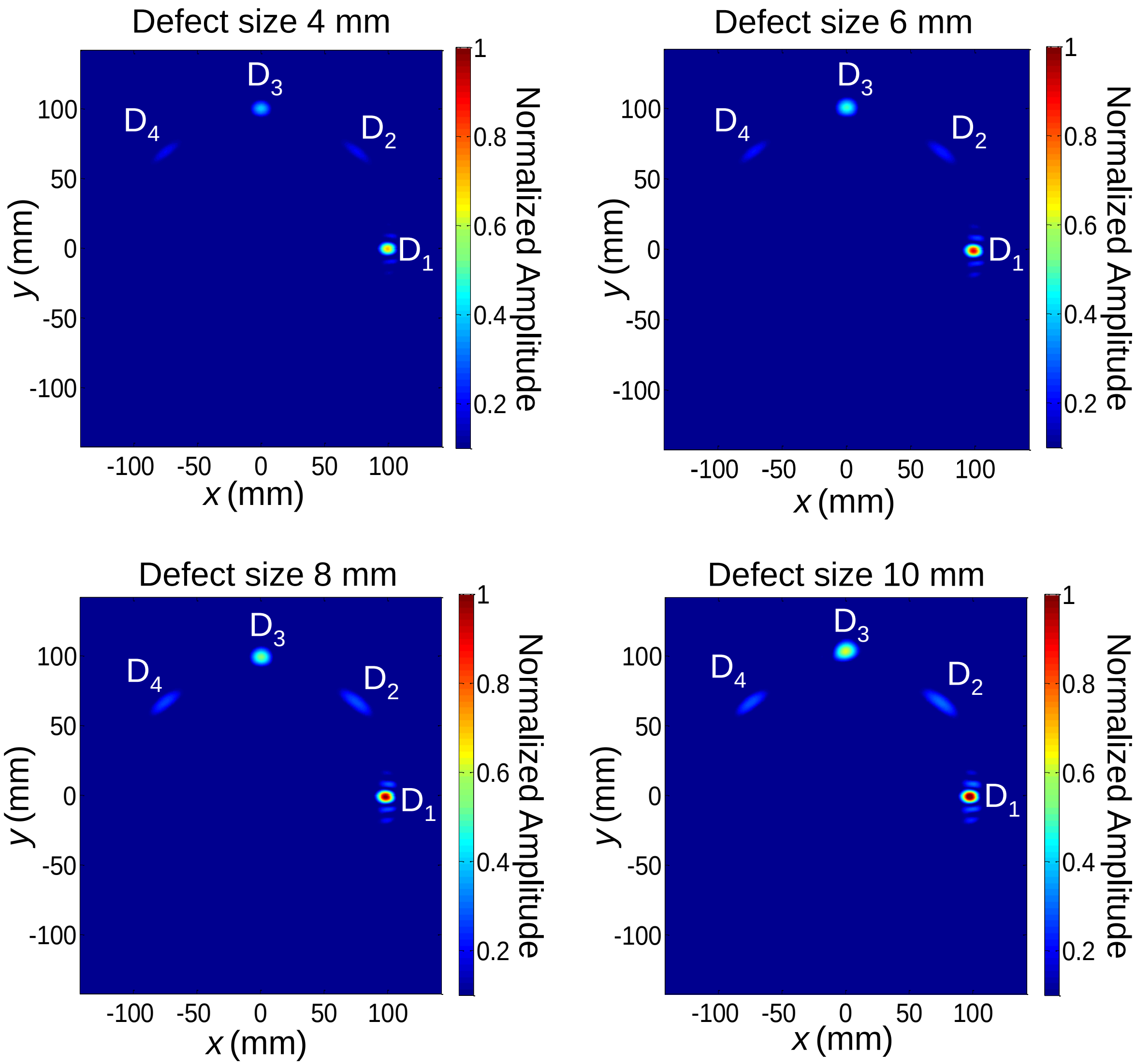
Time-space representation

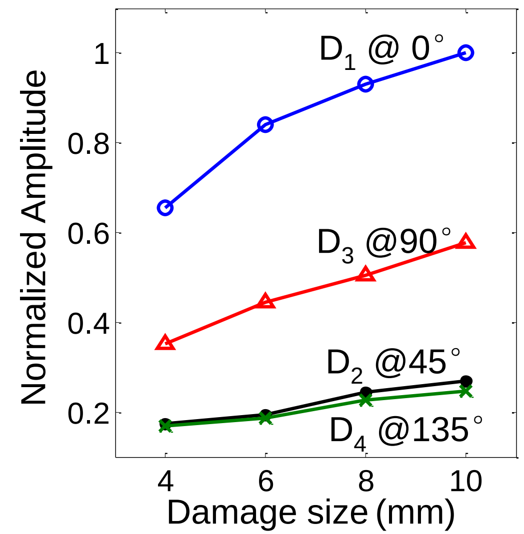
Detection Results

- 31×31 points are chosen from the scanning area to construct a phased array
  - Array configuration: 31×31 grid array
  - Element spacing: $d_x = d_y = 2$ mm
  - Array span: $D_x = D_y = 60$ mm



Detection of Multiple Defects in a CFRP Plate (Results)



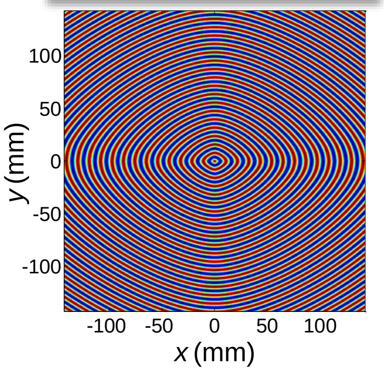


- Four defects are detected
- Location error < 4 mm
- Amplitude increases *w.r.t.* the defect size
- 0° > 90° > 45° (135°)

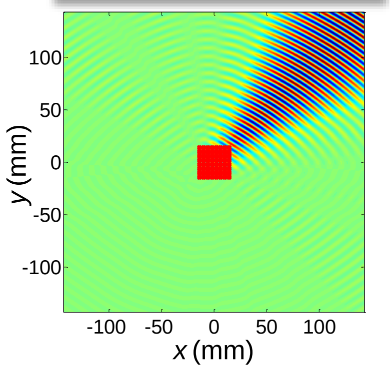
Conclusions

- Generic beamforming formula for anisotropic composites
  - Phase delay in frequency domain
  - Directionally dependent wavenumber and phase velocity are considered
  - The energy skew angle β between wavenumber vector **k** and group velocity vector $\mathbf{c}_g$ is considered
- Detection of multiple defects
  - The dispersion effect is compensated
  - Multiple defects are successfully detected
- Future work
  - Detect delamination damage
  - Enhanced beamforming
  - Directionally dependent wave amplitude A(θ)

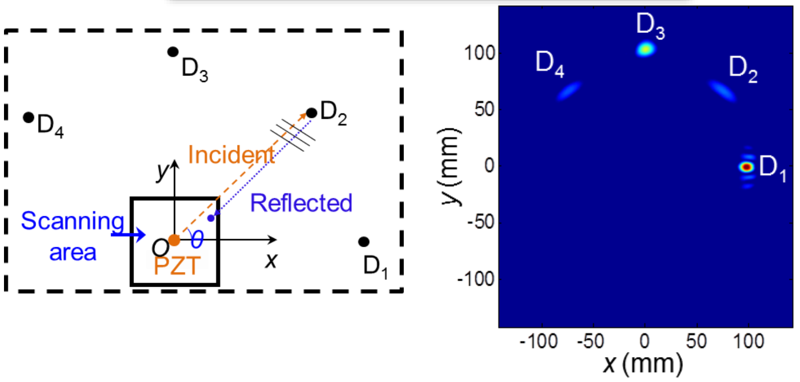
Wavefield of a single actuator



Beamforming result of an array



Detection of multiple defects



Acknowledgements

- The non-reimbursement space act umbrella agreement SAA1-18124 between South Carolina Research Foundation (SCRF) and the National Aeronautics and Space Administration (NASA) Langley Research Center
- SC NASA EPSCoR Research Grant Program 521192-USCYu

THANK YOU!
QUESTIONS?