Phased Array Beamforming and Imaging in Composite Laminates Using Guided Waves

Zhenhua Tian\textsuperscript{1}, Cara A.C. Leckey\textsuperscript{2}, Lingyu Yu\textsuperscript{1}

\textsuperscript{1} Department of Mechanical Engineering, University of South Carolina, Columbia, SC
\textsuperscript{2} Nondestructive Evaluation Sciences Branch, NASA Langley Research Center, Hampton, VA
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
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 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 \( \beta \) between wavenumber vector \( \mathbf{k} \) 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

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

**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: $11 \text{ mm} \geq \lambda_{y,\text{min}} \geq 8.0 \text{ mm}$
- Array configuration: $16 \times 16$ grid array
- Element spacing: $d_x = d_y = 2 \text{ mm}$

Point source at the origin

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

Array beamforming

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

Beamforming

Adjusting phase delay $\Delta_m(\theta_S)$
Beamforming Factor for Array Characterization

\[ BF(\theta | w_{p,q}, \theta_S) = \frac{1}{PQ} \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} w_{p,q} e^{j[k(\omega,\theta + \beta) - k(\omega,\theta_S + \beta_S)]} \left( p - \frac{P-1}{2} d_x, q - \frac{Q-1}{2} d_y \right) \]
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
Detection of Multiple Defects in a CFRP Plate (Setup)

- Test plate: 0.85 mm thick 8-ply CFRP plate with [0°/90°]s layup
- Defects: four quartz rods (D₁, D₂, D₃ and D₄) 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

SLDV points at selected locations \( \{ p_m \} \)

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
- $0^\circ > 90^\circ > 45^\circ \ (135^\circ)$
Conclusions

- Generic beamforming formula for anisotropic composites
  - Phase delay in frequency domain
  - Directionally dependent wavenumber and phase velocity are considered
  - The energy skew angle $\beta$ between wavenumber vector $\mathbf{k}$ 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 $A(\theta)$
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THANK YOU!
QUESTIONS?