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](http://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.
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

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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 $k$ and group velocity vector $c_g$ is considered

Point source at the origin

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

$m^{th}$ element at $\{p_m\}$

\[ u(t, x) = Ae^{j[\omega t - k \cdot (x - p_m)]} \]

Delay and sum beamforming

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

Delay $\Delta_m(\theta_S) = k(\omega, \theta_S + \beta_S) \cdot p_m$
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 Factor for Array Characterization

\[ BF(\theta \mid w_{p,q}, \theta_s) = \frac{1}{PQ} \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} w_{p,q} e^{j[k(\omega,\theta+\beta)-k(\omega,\theta_s+\beta_s)]} \left( (p--\frac{P-1}{2})d_x,(q--\frac{Q-1}{2})d_y \right) \]
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

\[
\begin{align*}
&x_1 \\
&x_2 \\
&y \\
&\theta \\
&D \\
&m^{th} \text{ scanning point at } p_m \\
&\text{Damage} \\
&\text{Incident} \\
&\text{Reflected} \\
&\text{Scanning area} \\
\end{align*}
\]
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 $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$

- PZT to generate guided waves
  - Excitation: 3-count tone burst at 90 kHz
- SLDV to measure wavefield in the scanning area
  - Dimensions: $45 \text{ mm} \times 45 \text{ mm}$
  - 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 \( \{ p_m \} \)

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 $A(\theta)$
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?