Composite Characterization using Ultrasonic Wavefield Techniques

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Overview

• Focus on NDE for Composites
• Noncontact Wavefield Methods
• NDE Simulation Tools
• Examples:
  • Delamination characterization
  • Waviness characterization
• Conclusion
Composites for Aeronautics

- **Advanced Composite Project** (5 Year Project):
  - Reduce timeline for certification of composite structures
  - Partnership: NASA, FAA, DoD, Industry, University

- **Rapid Inspection Technical Challenge**:
  - **Focus areas:**
    - Inspection of complex geometry components
    - Rapid large area inspection
    - Damage/defect characterization
    - Validation of detectability
  - **Damage types:**
    - Microcracking, fiber waviness, delamination, porosity
Composite Damage/Defect Types

X-ray CT data of microcrack damage

Micrograph showing resin rich regions and fiber misalignment

Fiber waviness (in-plane), i.e. marcelling
From Kugler and Moon 2002
doi: 10.1177/0021998302036012575

X-ray CT of PRSEUS Joint
From NASA TM-2013-217799 by Patrick Johnston

Micrograph showing porosity

X-ray CT data of delamination damage

Micrograph showing resin rich regions and fiber misalignment

UT data of delamination damage

2.5 mm

Voids

Delamination
Wavefield Methods

- GW’s easily generated in plate-like specimens due to boundaries
- Promise for covering large areas via long distance travel
- *Noncontact measurement* with Laser Doppler Vibrometry (LDV)
- Multi-beam LDV’s under development by commercial companies
- Simulation can aid in method development
  - Challenging to get representative experimental samples
  - Relying only on experiment is costly
  - Investigate larger number of scenarios
Ultrasound Simulation

- Elastodynamic finite integration technique ultrasonic simulation code
  - Custom C++ and MPI
  - Similar to finite difference
  - Adaptable, equations directly under our control
  - Output analogous to LDV wavefield data
Broader Need for NDE Simulation

• Simulation tools to model the physics of the NDE inspection are needed to enable:
  • Consideration of NDE during design stage, leading to less conservative designs
  • Feasibility to study a large number of damage scenarios to establish confidence in inspectability
  • Cost-effective development of optimal methodologies for advanced materials and structures
  • Computational NDE is likely the only cost-effective approach for structural health monitoring system validation
Wavefield Method Examples
Delamination Characterization

- 3D EFIT: 1.8 billion grid cells
  - 110 mm x 65 mm x 3.2 mm
- Run on 80 core 1TB shared memory machine
- Step size=23.4µm, $\lambda_{\text{min}}/64$

Impact side

NASA X-ray CT data of delamination damage

2.5”
Data Processing: Wavenumber Analysis

Local Wavenumber Analysis Technique:
1) 3D FT of Hann windowed wavefield, local window
2) Select 3D FT slice at excitation center frequency
3) Calculate dominant wavenumber of local window

Case 1:
- Full delam

Case 2:
- Hidden delam removed

Case 3:
- Half delam removed

Experimental Results

• Multi-frequency wavenumber analysis

1 Juarez, P. and Leckey, C. “Multi-frequency Local Wavenumber Analysis and Ply Correlation of Delamination Damage”. Submitted to Ultrasonics
Can this be applied to other defects?

Cases where traditional C-scan may not work well?
Wrinkling and Waviness

- Wrinkling (OOP) and waviness/marcelling (IP) can be created during fabrication - layup and cure (e.g. uneven curing and resin shrinkage)
- Strength affected by both
  - Wrinkling more readily visible to the eye, can readily occur in complex joints and be converted to in-plane waviness during fabrication


Image From: Kugler and Moon, “Identification of the most significant processing parameters on the development of fiber waviness in thin laminates” J Composite Materials (2001)

Fig. 6. Initial fibre wrinkles convert to in-plane fibre waviness after curing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Waviness

• IP more likely to occur in thin laminates and OOP more likely in thick laminates
• In-plane waviness can lead to microbuckling, kinking, and matrix cracking (Berbinau 1999, Jumahat 2010)
• More difficult to create representative samples with this defect
• Simulation studies enable analysis of ultrasound effects from in-plane waviness
Noncontact Methods: Waviness?

- Literature reports changes in group velocity\(^1\) of guided waves
  - 15° fiber wave \(\rightarrow\) 4% change velocity (fairly small change)
- Other wave changes might be detected with advanced processing methods

Modeling of Waviness

• Individual fibers are not modeled, but $C_{ij}$ matrix defined at each grid position

\[
\begin{pmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\
C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{pmatrix}
\]

Rotation matrix

\[
\begin{pmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 & C_{16} \\
C_{21} & C_{22} & C_{23} & 0 & 0 & 0 & C_{26} \\
C_{31} & C_{32} & C_{33} & 0 & 0 & 0 & C_{36} \\
0 & 0 & 0 & C_{44} & C_{45} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{55} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{pmatrix}
\]
In-plane waviness

- Representative waviness amplitudes in CFRP, wavelength determined from literature (Mizukami 2016, Fuhr 2013)

Reported Young’s modulus reduction of ~65% for CFRP uni
**Unidirectional, Top ply wavy**

- 8-plies, top ply contains waviness
- Observe change in wave directionality (human eye good at picking it out)
- Observable at both surfaces
- Try methods for automated data processing

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![Diagram of wave orientation and measurement](image)
Unidirectional, Top ply wavy

\[ \sim 0.5\lambda \text{ waviness} \]
Unidirectional, Top ply wavy
Crossply, Top ply wavy
Unidirectional: Wavenumber Analysis

- 3DFFT performed to study modes, directional wavenumbers, and associated amplitudes
- Shows presence of waviness and quadrants, but requires background subtraction and does not show specific spatial location or characterization information
- Would like automated processing to locate waviness, and ideally characterize it
Crossply: Wavenumber Analysis

Nondestructive Evaluation Sciences Branch
Conclusion

• Wavefield methods have potential for rapid inspection and large area coverage
• Limitations/capabilities of the method still being explored
• Simulation can aid development of methods for detecting and characterizing composite damage/defects
Questions?
Computational Benefit

- Need rapid, realistic NDE simulation capabilities to have a practical tool
- Advanced computing architectures continue to emerge
- In-house code adaptable to various computer architectures
  - Computing clusters
  - GPU and Many integrated core (e.g., Intel Xeon Phi)
- Phi Example: ~10X faster, ~0.6% cost
Validation

- Validation is a key step
- Use Laser Doppler Vibrometry for direct comparisons to experiment

Approximate time=56 microseconds after initial excitation
Off-angle example: Out-of-plane

30 degree orientation

0 degree orientation
Off-angle example: In-plane

- For some cases, comparisons with theory (required due to 1-D LDV)
Composites for Space

SLS Architecture Reference Configuration

- Launch Abort System
- Orion
- Interim Cryogenic Propulsion Stage (ICPS)
- Interstage
- Solid Rocket Boosters
- Core Stage
- Upper Stage
- 130t 244 ft
- 70t 321 ft
- RS-25 Engines