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
- Micrograph showing porosity
- X-ray CT data of microcrack damage
- X-ray CT data of delamination damage
- UT data of delamination damage
- X-ray CT of PRSEUS Joint
  From NASA TM-2013-217799 by Patrick Johnston
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, \( \lambda_{\text{min}} / 64 \)
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,

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 → 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.

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

Rotation matrix

$$
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\
C_{21} & C_{22} & C_{23} & 0 & 0 & C_{26} \\
C_{31} & C_{32} & C_{33} & 0 & 0 & C_{36} \\
0 & 0 & 0 & C_{44} & C_{45} & 0 \\
0 & 0 & 0 & C_{54} & C_{55} & 0 \\
C_{61} & C_{62} & C_{63} & 0 & 0 & C_{66}
\end{bmatrix}
$$
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
Unidirectional, Top ply wavy

~0.5\(\lambda\) 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
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
- RS-25 Engines
- Upper Stage
- Core Stage
- Advanced Boosters
- 130t
- 70t 321 ft

Composite Cryotank

Composite Booster

Orion Composite Crew Module

25 ft