Full wave field signal processing for NDT of composites

Joost Segers, Mathias Kersemans, Erik Verboven, Saeid Hedayatrasa, Gaétan Poelman and Wim Van Paepegem

SIM-SBO Project M3DETECT-IV

Partners:
Introduction

Composite materials are GREAT!

But also challenging…
- Complex fabrication
- High cost (CFRP)
- Susceptible to internal defects/damages

High specific strength
- Resistance to fatigue and corrosion
- Design flexibility

Accurate non-destructive testing (NDT) technique needed!

→ What about using Lamb waves?
Presentation Overview

1. What are Lamb waves? And how can we use them for NDT of composites

2. Case study 1 – CFRP coupon with 1 flat bottom hole

3. Case study 2 – CFRP coupon with >1 flat bottom holes

4. Case study 3 – A400M flat component with internal damage

5. Conclusions
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5. Conclusions
1. What are Lamb waves?

Lamb waves = elastic waves travelling in solids, guided by the surfaces

**Material**
- Density
- Elastic tensor
- Local thickness

**Excitation**
- Frequency
- Type: burst, sweep
- Location

**Waves**
- Mode type
- Wavenumber
- Group velocity
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Defect = change in density and/or elastic tensor and/or thickness
→ Change in guided wave modes
1. Lamb waves for NDT of composites

Defect = change in density and/or elastic tensor and/or thickness
→ Change in guided wave modes

Comparable with waves on water hitting a rock (=defect)
1. Lamb waves for NDT of composites

Defect = change in density and/or elastic tensor and/or thickness

→ Change in guided wave modes

- Wave scattering
- Wave mode conversion
- Wave amplification
- ...

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1. Lamb waves for NDT of composites

Defect = change in density and/or elastic tensor and/or thickness
→ Change in guided wave modes e.g. scattering
→ Measure full wavefield using 3D scanning laser Doppler vibrometer
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Case 1: CFRP plate with FBH @ 50 kHz

CFRP 
\[ [(45/0/-45/90)]_{3s} \]

Flat bottom hole
Diam. 15mm
Depth 2mm

PZT actuator

5 cycle Gaussian burst

50 kHz center freq.

CFRP plate dimensions:
- Length: 330 mm
- Width: 330 mm
- Thickness: 5.52 mm

50 kHz center frequency Gaussian burst signal.
Case 1: CFRP plate with FBH @ 50 kHz

CFRP plate with dimensions 330 mm x 330 mm and thickness t = 5.52 mm. The plate consists of the laminate [(45/0/-45/90)]_3s. It contains a flat bottom hole (FBH) with a diameter of 15 mm and a depth of 2 mm. The SLDV measurement results indicate a single wave mode, wave reflection, wave scattering, and wave amplification. 

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M³ Macro Model Mat
Ghent University - Department of Materials, Textiles and Chemical Engineering
Joost Segers
Case 1: CFRP plate with FBH @ 50 kHz

CFRP 
\([(45/0/-45/90)]_3s\)

Flat bottom hole
Diam. 15mm
Depth 2mm

SLDV measurement results
- Wave scattering
- Wave amplification
- Wave reflection
- Single wave mode

\[ t = 5.52 \text{ mm} \]
Case 1: CFRP plate with FBH @ 50 kHz

CFRP

\[ [(45/0/-45/90)]_3 \]

Flat bottom hole
Diam. 15mm
Depth 2mm

330 mm
330 mm
t = 5.52 mm

Wave scattering
Wave amplification

SLDV measurement results

\[ WRMS(x, y) \approx \sqrt{\frac{1}{N} \sum_{k=1}^{N} s(x, y)^2 \cdot n^k} \]
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Case 2: CFRP plate with FBHs @ 150 kHz

CFRP [(0/90)]₆s

Multiple FBHs

330 mm

5 cycle Gaussian burst

@ 150 kHz

t = 5.52 mm
Case 2: CFRP plate with FBHs @ 100 kHz

CFRP plate with multiple FBHs. Dimensions: 330 mm x 330 mm, thickness t = 5.52 mm.

CFRP plate: [(0/90)]₆s.
Case 2: CFRP plate with FBHs @ 100 kHz

330 mm

330 mm

t = 5.52 mm

CFRP

[(0/90)]₆s

Multiple FBHs

S₀ mode

A₀ mode
Case 2: CFRP plate with FBHs @ 100 kHz

Separate both modes using filtering in frequency wavenumber domain

- Raw measurement
- A0 mode
- S0 mode
Case 2: CFRP plate with FBHs @ 100 kHz

Separate both modes using filtering in frequency wavenumber domain

Raw measurement

Mode conversion

$S_0 \rightarrow A_0$

A0 mode

S0 mode
Case 2: CFRP plate with FBHs @ 100 kHz

Separate both modes using filtering in frequency wavenumber domain.

- Raw measurements
- A0 mode
- S0 mode

Wave amplification
Wave reflections
Case 2: CFRP plate with FBHs @ 100 kHz

Final step: Get a map of the defects
→ Remove both ‘virgin’ A0 and S0 mode
   = Keep only wave/defect interactions
→ Calculate the (weighted) average over time
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Case 3: A400M flap skin

Airbus A400M flap skin with production defects provided by SABCA Limburg
Defects detected (and marked) using ultrasonic C-scan

Reliable
Slow
Case 3: A400M flap skin

Burst excitation with center frequency 150 kHz

- Fast S0 wave, slow A0 wave
- Mode conversion at stiffeners
- Different wave characteristics at stiffeners
- Defect/wave interactions?
  → Filter out the A0 and S0 waves travelling in sound material
Case 3: A400M flap skin

Burst excitation with center frequency 150 kHz

Raw measurement

Filtered measurement
Case 3: A400M flap skin

Damage map using weighted root mean square calculation
Case 3: A400M flap skin

Damage map using weighted root mean square calculation

Thermography
3. Conclusions

- Lamb waves are travelling elastic waves guided by the component’s surfaces.
- Lamb waves interact with defects in multiple ways e.g. scattering, mode conversion,…
- Advanced wave mode filtering can be used to calculate a damage map.
- Both artificial as well as realistic defects were successfully detected.
Thank You

ir. Joost Segers
PhD Researcher
Mechanics of Materials and Structures
Ghent University
e-mail: joost.segers@ugent.be

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