Composite characterization using laser Doppler vibrometry and multi-frequency wavenumber analysis

By Peter Juarez and Dr. Cara Leckey

NASA Langley Research Center
Nondestructive Evaluation Sciences Branch
Motivation

Composite Solutions Applied Throughout the 787

- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons

50% Composites
15% Titanium
20% Aluminum
10% Steel
5% Other

Boeing Dreamliner
Barely Visible Damage (BVD)
IM7/8552(1D) 15 x 15 2G-Ply

[(0/45/-45/90)]
Motivation

Carbon fiber composite

Low velocity impact

Ply layers
• 26 ply carbon fiber panel 15”x15”, quasi-isotropic layup ([0/45/-45/90]_3/0)_s

• Damaged using a static point load of 1511 lbf until failure, then scanned using a traditional nondestructive evaluation technique (ultrasonic immersion tank scanning)
Normal to YZ plane

Normal to XY plane

Next: Goals
Goal of research

• Data was collected from a Scanning Laser Doppler Vibrometer (SLDV) while acoustic waves were excited in the panel with a contact transducer

• Goal: to correlate the SLDV data to the size and depth of the delaminations in the composite
What are we detecting?
What are we detecting?

Lamb wave

$\frac{1}{\text{wavelength}} = \text{wavenumber}$
What are we detecting?

Delamination
Any relationship between wavenumber and location is lost.
Local wavenumber technique

Wavefield data over time

Time

X (mm)

Y (mm)
Local wavenumber technique

Wavefield data over time

FFT

Wavefield data over frequency
Local wavenumber technique
Local wavenumber technique
Local wavenumber technique
Local wavenumber technique

2D FFT

X
Y

k_x
k_y
Local wavenumber technique
Local wavenumber technique

2D FFT

$X$ $Y$

$X$ $Y$

$k_x$ $k_y$
Local wavenumber technique

2D FFT

k_x

k_y
Local wavenumber technique
Window size

![Image of a 3D plot with color scale and axis labels (x in mm on the bottom and y in mm on the left)]

- **x** (mm) range: 3 to 66
- **y** (mm) range: 3 to 66
- Color scale: 150 to 350

**5mm Scale**
Window size
Window size
Dechirp process

Data recorded using chirp excitation

Chirp Excitation Signal

Desired single frequency signals

\[ u(x, y, t) = \mathcal{F}^{-1} \left[ \frac{\mathcal{F}(R_c(x, y, t))}{\mathcal{F}(S_c(x, y, t))} \star \mathcal{F}(S_d(x, y, t)) \right] \]

Single frequency excitation data

Nondestructive Evaluation Sciences Branch
Differences in frequencies: Wavefields

![Wavefields images]

- 200kHz
- 300kHz
- 400kHz
- 500kHz
Differences in frequencies: Wavenumber

350kHz

400kHz

450kHz

500kHz

550kHz

750kHz
Nondestructive Evaluation Sciences Branch

Frequency

Wavenumber

Next: Curve correlation
Multi-frequency wavenumber-ply correlation

\( k(x, y, f_1) \)

\( k(x, y, f_2) \)

\( k(x, y, f_3) \)

\( k(x, y, f_4) \)
Multi-frequency wavenumber-ply correlation
Multi-frequency wavenumber-ply correlation

\[ k_1, k_2, k_3, k_4 \]

\[ f_1, f_2, f_3, f_4 \]

\[ \text{Ply}_1, \text{Ply}_2, \text{Ply}_3, \text{Ply}_4 \]
Multi-frequency wavenumber-ply correlation
Multi-frequency wavenumber-ply correlation

\[ \text{Ply}(x, y) \approx \text{Ply}_2 \]
Ply correlation results

- Correlation frequency range: 300kHz-400kHz in 5kHz steps
- 10mm window
- 0.3mm spatial resolution
- 20MHz sampling rate
Ply correlation results

Next: Dispersion curve
Sources of error: standard deviation
Sources of error: dispersion curves
Conclusions

- The local wavenumber technique is capable of very accurate determination of the shape and size of interlaminar damage in composite panels, especially when considering multiple frequencies.
- Using multi-frequency wavenumber-ply correlation can determine the depth location of damage in many instances, but struggles with deeper and smaller delaminations.
- Future research will be conducted to improve this methodology using wave domain filtering, better dispersion curve generation, and more robust correlation methods.
References

I.M. Daniel, O. Ishai


M. Richardson, M. Wisheart


B. Li, Y. Liu, K. Gong, Z. Li

Z. Liu, F. Yu, R. Wei, C. He, B. Wu


M.D. Rogge, C.A. Leckey
Characterization of impact damage in composite laminates using guided wavefield imaging and local wavenumber domain analysis Ultrasonics, 53 (7) (2013), pp. 1217–1226


T.E. Michaels, J.E. Michaels, M. Ruzzene

Z. Tian, L. Yu, C. Leckey

C.A. Leckey, M.D. Rogge, C.A. Miller, M.K. Hinders
Multiple-mode lamb wave scattering simulations using 3d elastodynamic finite integration technique Ultrasonics, 52 (2) (2012), pp. 193–207

C.A. Leckey, M.D. Rogge, F.R. Parker

H. Sohn, D. Dutta, H. Yang, M. Park, M. DeSimio, S. Olson, E. Swensen
References

C.A.C. Leckey, J. Seebo
Guided wave energy trapping to detect hidden multilayer delamination damage

E.B. Flynn, S.Y. Chong, G.J. Jarmer, J.-R. Lee
Structural imaging through local wavenumber estimation of guided waves
NDT & E Int., 59 (2013), pp. 1–10


J.E. Michaels, S.J. Lee, A.J. Croxford, P.D. Wilcox
Chirp excitation of ultrasonic guided waves

V. Herb, G. Couégnat, E. Martin
Damage assessment of thin SiC/SiC composite plates subjected to quasi-static indentation loading

G. Williams, R. Trask, I. Bond
A self-healing carbon fibre reinforced polymer for aerospace applications

V.V. Bolotin
Delaminations in composite structures: its origin, buckling, growth and stability

G. Clark
Modelling of impact damage in composite laminates

B. Pavlakovic, M. Lowe, D. Alleyne, P. Cawley
Disperse: a general purpose program for creating dispersion curves