DAMAGE DETECTION IN COMPOSITE CYLINDERS USING MODULATED GUIDED WAVE VIBRATION

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Outline

- Introduction of IAI and Projects
- Background and Motivation
- Objectives
- Method and Assumptions
- Procedure
- Preliminary Results and Discussion
- Conclusion
- Acknowledgment
Intelligent Automation Inc.

**Company Overview**
- Woman-owned small business
- Founded in 1987
- Headquartered in Rockville, MD
- 125 Professional staff
- $23M revenue for 2010
- Won twice the Small Business “Tibbetts Award” (2000, 2007)

**Organization**

- **Sensors, Signals and Systems Division**
  - Control and Signal Processing
  - Communications and Sensors
  - Robotics & Electromechanical Systems

- **Distributed Intelligent Systems Division**
  - Multi Agent Systems
  - Networks and Security
  - Air Traffic Management

- **Education & Training Technology Division**

**IAI Strengths**
- Sustained record of excellence in R&D
- Strong qualifications in supporting large DOD and NASA programs through primes
IAI’s Experience in NDE Sensors, Simulation, and Systems

- **Sensors**
  - Ultrasonic guided wave transducers
  - EMAT (SH wave, Lamb wave, bulk wave)
  - Wireless ultrasonic transducer node
  - Piezoelectric sensor network for SHM
  - Sol-gel piezoelectric transducer patch
  - Hybrid Tap Tester (AE, Microphone)
  - Scanning acoustic microscope, eddy current system, 2D scanner, air coupled probes

- **Algorithm/Simulations**
  - Guided wave simulation toolbox
  - Statistical ultrasonic guided wave tomography
  - Physics of failure simulation

- **NDE/SHM Systems**
  - Impact echo
  - Ultrasound
  - Guided waves
  - Nonlinear acoustics
  - Acoustic emission
  - Eddy current
  - RF reflectometry
  - Digital shearography
  - Microwave/Terahertz
  - Wireless sensor networks
Motivation of the R&D

- Composite rocket motor cases are subject to damage due to fatigue, mechanical impact, and aging in a service environment.
- Early detection of these failures is desired for improving structure safety. Detection of tiny cracks are important!
- Current NDI methods for composites are limited to flat or nearly flat composite plates.
- A real-time hand-held NDI system is desired to detect defects in both flat and curved composite structures.
- We propose a nonlinear guided wave imaging (NGWI) technique for detecting small incipient damages in complex composite structures. Higher sensitivity than its linear counterpart.
Introduction: Nonlinear Ultrasound

$$\sigma = \rho_0 c_l^2 \left( \varepsilon + \beta \varepsilon^2 + \gamma \varepsilon^3 + \ldots \right)$$

\(\sigma\) - stress, \(\varepsilon\) - strain, \(\beta, \gamma \ldots\) - non-linear parameters (quadratic nonlinearity, cubic nonlinearity, etc…)

\(\rho_0\) - density, \(c_l\) - speed of longitudinal elastic wave

Nonlinearity may be ten times higher for media with cracks and flaws!

Nonlinear Elastic Wave Modulation Spectroscopy

The crack stiffness $\sigma = K(\xi)\xi$

$K = K_0 + \beta \xi$

$\sigma = K_0 \xi + \beta \xi^2$

Simple, but effective and sensitive!
Cross-modulation Test Setup

No crack = No modulation

Crack presence provides modulation (\( f_+ \) and \( f_- \) sidebands)

Example setup

Signal generator \( f_1 \)

Power amplifier

Vibrator

Signal generator \( f_2 \)

Processing block

transducers

Tested part

Computer

\( f_1 \)

\( f_2 \)

Low frequency

High frequency

\( f_1 \)

\( f_2 \)

Low frequency

High frequency

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Example Samples Tested
Introduction: Ultrasonic Guided Waves

Guided waves are elastic waves propagating in solid media with boundaries. Since wave energy is trapped in between boundaries, it can travel a long distance, thus suitable for long range inspection. Multiple wave modes may exist in a structure, which can be represented as dispersion curves as shown here.

Calculated phase velocity dispersion curves for circumferential guided waves traveling in 0° fiber direction.

Wave structures for wave mode #3 (the red line) at 238 kHz.

Example 8-layer (90/45/-45/0)\textsubscript{s} composite pipe.
Nonlinear Guided Wave Modulation Spectroscopy

- Combining ultrasonic guided waves for **fast scanning capabilities** with nonlinear acoustic technique for **enhanced sensitivity**

- Potentially no need for baselines

- Simple extension of current signal processing technologies for guided waves

- Applicable to both metallic and composite materials
ABAQUS FEM simulation was performed for nonlinear guided wave modulation.

Input:
30kHz+300kHz continuous wave.

3m-long 2mm-thick Al Plate in good condition

Received signal

Spectrum of received signal

No side bands
Nonlinear Guided Wave Modulation Simulation (Cont’d)

Input:
30kHz+300kHz continuous wave.

3m-long 4mm-thick Al Plate

3mm crack

Received signal
Spectrum of received signal

Strong modulations!

\( f_2 - f_1 \)  \( f_2 + f_1 \)
Example Nonlinear Guided Wave Test Setup

Fatigue crack from a rivet hole (0.25" in length)
Spectrum Results

The collected signal spectrum clearly shows the presence of crack in the plate!

The spectrum for the Aluminum sample with fatigue cracks measured with sensor pair 1-4.

The spectrum for the Aluminum sample with fatigue cracks measured with sensor pair 2-4.

The collected signal spectrum clearly shows the presence of crack in the plate!
Feasibility Study on Composite Plates

C-scan of the composite plate showing damage area.

Experimental setup

Modulation side bands indicating damages
NGWI Experimental System Architecture

Nonlinear Guided Wave Imaging System for Damage Detection
Filament Wound Composite Cylinder Specimens

- 6” inner diameter quasi-isotropic carbon/epoxy cylinders layup [±30/90]_3, thickness 4.17 mm

- Double layer rectangular 76.2-micron-thick Teflon sheets embedded as flaws.

- The carbon fiber used was Toray (Flower Mound, TX) T700S-24K. The matrix material was EPON 862 with EPIKURE W curative mixed together in a 100:26.4 ratio with 100% stoichiometry respectively. The approximate fiber volume fraction was set at 0.63
Sample Description

Teflon a is located between Plies 1 and 2; Teflon b, d, and e are between Plies 3 and 4; c is between Plies 5 and 6.
Guided Wave Modeling for the Composite Cylinder

Estimated material properties of T700/862 unidirectional lamina for $V_f = 0.63$.

<table>
<thead>
<tr>
<th>Elastic Properties</th>
<th>Dens.</th>
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<tr>
<td>$E_{1T}$ GPa</td>
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<tr>
<td>$E_{1C}$ GPa</td>
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</tr>
<tr>
<td>$E_2$ GPa</td>
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<td>$\nu_{12}$</td>
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<td>$\nu_{23}$</td>
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<tr>
<td>$G_{23}$ GPa</td>
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<tr>
<td>$\rho$ kg/m$^3$</td>
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</table>

Low frequency guided wave was chosen for stronger energy penetration and simple signal interpretation.
FEM Simulation for Delamination Detection

delamination between ply 1 and ply 2

Guided wave around 110 kHz is most sensitive to delaminations!
Fabricated Transducer Array Based on Simulation

Hand-held, conformal, and easy to use!
Typical Guided Wave Inspection Result

Through transmission waveform

Damage inspection results

Array channels
No damage
Delamination
Guided Wave Damage Detection Algorithm

- Damage blocks wave propagation which leads to lower transmission of energy
- Calibration was performed for channel difference compensation. **No baseline is needed** for each individual cylinder.
- Ultrasonic couplant effect was considered, self-checking to ensure good coupling to composite
- Repeatability test: determine statistically the sensitivity levels of sensor array for damages
- Validation. Impact with a hammer and find damage
Can detect and locate impact delaminations in the composite cylinder

Big Teflon film defect (1” square, to simulate artificial delamination) can be detected

Small Teflon defect (0.5” square) poses some challenges, but with further signal processing, we should be able to detect it

Sample preparation is important for assessing the sensitivity
Integration of Guided Wave with Nonlinear Acoustic Technique

- PC software
- Power amplifier
- Multiplexer box
- Guided wave array
- LF vibrator
- Signal generator
- LF vibrator
Test Results for Impact Delamination

Side bands is clearly seen in for the damage!

No LF excitation

With LF excitation
Test result for damage localization

Impact site

Guided wave
Array

LF vibrator

Result spectrums

Most notable modulations!

Damage localization capability is good!
Nonlinear Guided Wave Modulation Result Discussion

- Sensitive to “breathing” surface touching cracks
- Did not detect embedded Teflon films, useful for differentiating damage types
- Need frequency tuning to “open up” damages
- Challenges for boundary touching parts
- Guided wave modes & nonlinearity?
Conclusions

- Guided wave and nonlinear acoustics technique can both detect and localize cracks/damages. Integration of the two techniques provides enhanced capabilities for field inspection composite SRM cases.

- A prototype hand-held transducer array system has been fabricated with the assistance of our guided wave inspection simulation tool. Lab testing has demonstrated the effectiveness of the system for impact damage detection.

- Sensitivity study of guided waves showed that delamination of 0.5” in diameter and cracks of 0.1” can be detected reliably.

- Nonlinear acoustics showed good detection capability, and it can enhance the guided wave inspection accuracy by providing the modulation spectrum and verifications.
Acknowledgment

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Thank You and Questions?
Innovative solutions to meet your technical challenges ….