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Nonlinear Ultrasonic NDE

Francesco Ciampa, Michele Meo

Department of Mechanical Engineering,
University of Bath, Bath, BA2 7AY, UK.
Outline

• Need for Nonlinear Ultrasonic NDE Methods
• Nonlinear Imaging Method
• 3D Multiscale Model for Nonlinear Wave Propagation
• Experimental and Numerical Results
Need for Nonlinear Ultrasonic NDE Methods

- Reflection and scattering of primary waves at heterogeneities and discontinuities are measured
  - They work satisfactory for high acoustic impedance contrast
  - No changes of input frequency but only amplitude and phase variations

- Micro-damages and changes in constitutive parameters (elastic moduli, sound speed) are too sensitive to be detected by linear ultrasonic techniques
Need for Nonlinear Ultrasonic NDE Methods

Linear Acoustic/Ultrasonic NDE Methods

Nonlinear Acoustic/Ultrasonic NDE Methods
Material Anharmonic Effects

- Materials such as aluminium steel, glasses, single crystals and numerous others exhibit anharmonic effects when damaged (classical nonlinear theory, CNL).

- They can be expressed by a nonlinear strain-stress relationship (Landau’s Theory).
- Using mono- or bi-harmonic excitation the interaction of the ultrasonic waves with the structural damage generates new frequency components (Even Harmonics).
Material Hysteretic Effects

- Materials such as rock, soil, ceramics, concrete, but also damaged composite and metal structures manifest *biphasic nature* (hard grains and soft bond systems), i.e. micro-damage zones with *hysteretic nonlinearity* (*non-classical nonlinear theory*, NME)
- Physical dynamic models attribute this nonlinear behaviour to friction of crack surfaces (closure and opening of crack or a bond system)
- The nonlinear effect on the wave propagation is to create **Odd Harmonics**
Nonlinear NDE Ultrasonic Imaging Method

Damaged zone “focusing area” divided in a grid of $M=7 \times 6$ “excitation points”

- **Third order nonlinear response** using **Phase Symmetry Analysis (PSA)** with chirp excitation and **Inverse Filtering (IF)**

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**Ciampa, F., Meo, M.** Nonlinear elastic imaging using reciprocal time reversal and phase symmetry analysis. *Journal of Acoustical Society of America, 130* (6), pp. 4316-4323, 2012
Nonlinear Inverse Filtering

- In a Inverse Filtering (IF) process an input signal is *focused back* on the nonlinear source if the output received by the transducer is *reversed* in time and emitted back to the excitation point.

- The *reverberant diffuse wave field* (boundary reflections, mode conversion) in a geometrically complex medium enhances the spatial focusing of the re-emitted signals (*Kaleidoscopic effect*).

- Only one receiver sensor can be used for optimal refocusing.
Nonlinear Third Order Imaging Results

Receiver and damage coordinates

<table>
<thead>
<tr>
<th></th>
<th>X-coordinates [cm]</th>
<th>Y-coordinates [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver position (case T1)</td>
<td>60</td>
<td>17</td>
</tr>
<tr>
<td>Receiver position (case T2)</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>Damage location</td>
<td>38</td>
<td>24</td>
</tr>
</tbody>
</table>

Case T1

Case T2

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Nonlinear Second Order Imaging Method

- CFRP
- 153 x 106 x 3 mm
- [0/45/90/-45]$_s$
- BVID @ 10 J

Damaged zone “focusing area” divided in a grid of $M=8 \times 5$ “excitation points”

- **Second order Nonlinear Response** using Phase Symmetry Analysis

Measured Signal

Second Order Response with PSA
### Receiver and damage coordinates

<table>
<thead>
<tr>
<th></th>
<th>X-coordinates [mm]</th>
<th>Y-coordinates [mm]</th>
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</thead>
<tbody>
<tr>
<td>APC sensor (case S1)</td>
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</tr>
<tr>
<td>MFC sensor (case S2)</td>
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<tr>
<td>Damage location</td>
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</tbody>
</table>

**Nonlinear Second Order Imaging Results**

**Case S1**

**Case S2**

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Multiscale FE Model for Nonlinear Wave Propagation

- **Multiscale material model** implemented in Finite Element (FE) able to simulate the nonlinear interaction of ultrasound waves with cracks/damage precursors.

  In the Multiscale model, intermediate (mesoscopic) material elements are introduced between the **microscopic** mechanics (micro-cracks, grain size, etc...) and the **macroscopic** structural behaviour.

- Nonlinear effects can be simulated:
  - **Odd harmonics** – material hysteresis and discrete memory such as concrete, ceramics, sandwich structures, etc...
  - **Even Harmonics** – material anharmonic effects such as fatigue damage in metallic materials and delamination in multi-layered structures.
3D Numerical Results for a composite bar with in-plane harmonic wave propagation ($f_0 = 100$ kHz)

Crack dimensions = 2 x 12 x 8 mm

$f(t) = A \sin(2\pi ft)$

Second Harmonic

Third Harmonic

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Numerical Results – Isotropic and Composite Bar

Isotropic

Composite
Numerical and Experimental Results – Composite Panel

X-Ray Tomography

Second Harmonic

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For Further information:

Francesco Ciampa

Department of Mechanical Engineering,
University of Bath, Bath, BA2 7AY, UK.

f.ciampa@bath.ac.uk

Thank you for your attention!!