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Nonlinear Ultrasonic NDE

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Outline

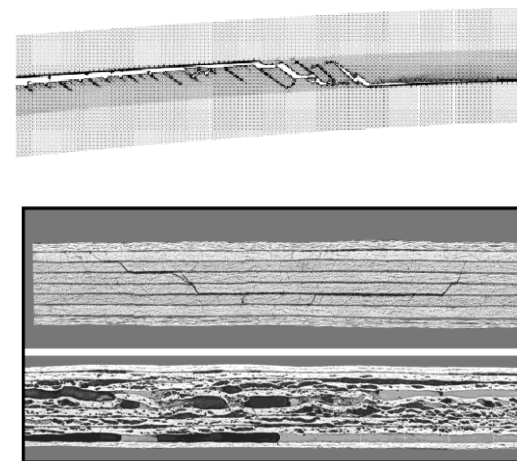
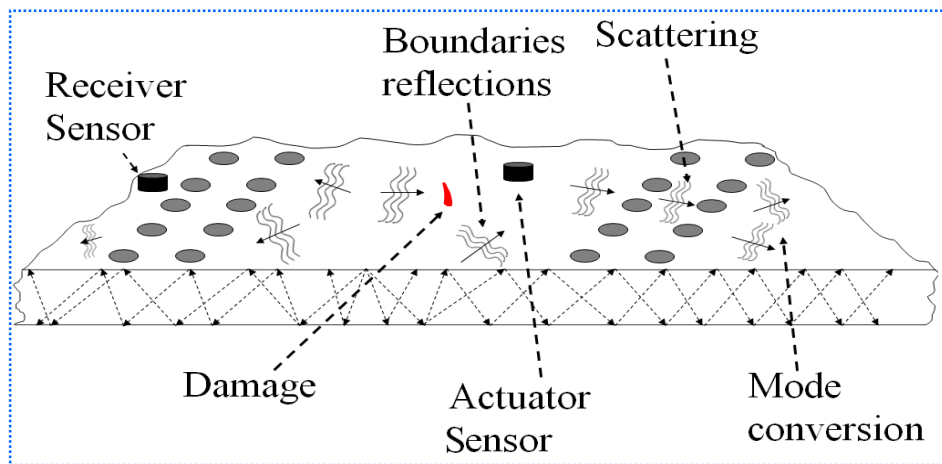


- Need for Nonlinear Ultrasonic NDE Methods
- Nonlinear Imaging Method
- 3D Multiscale Model for Nonlinear Wave Propagation
- Experimental and Numerical Results

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

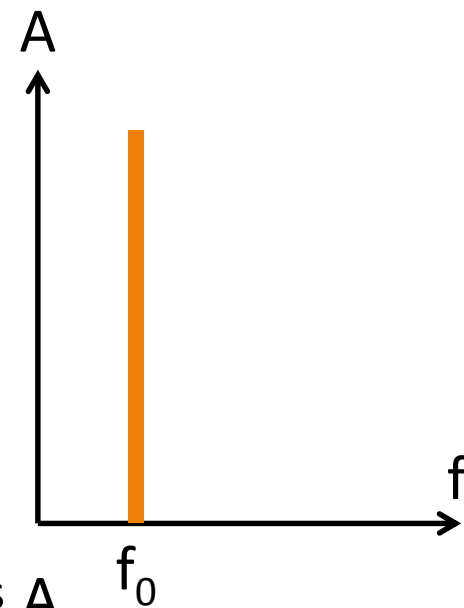
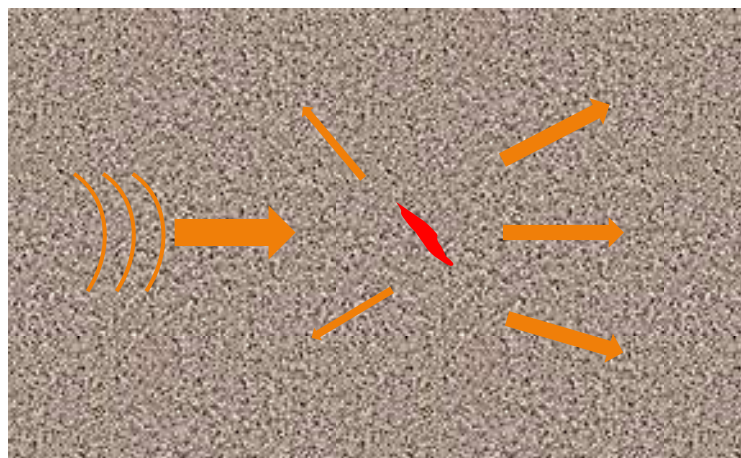
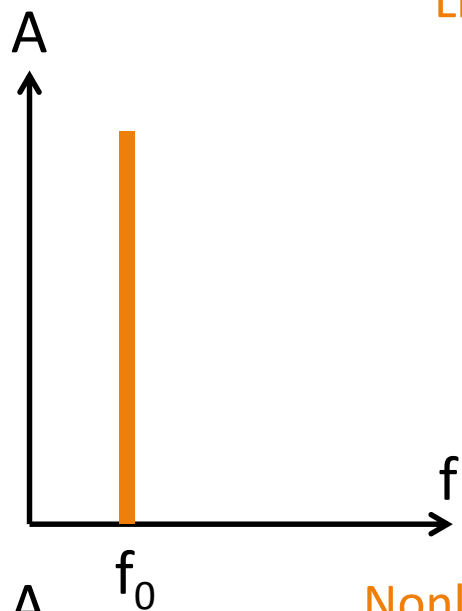
Delamination in multi-layered materials



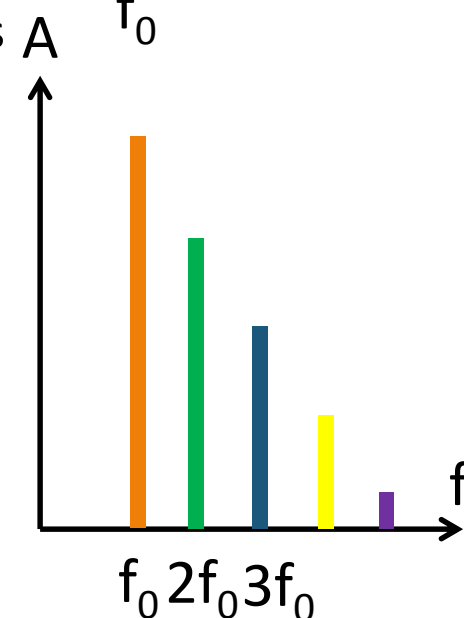
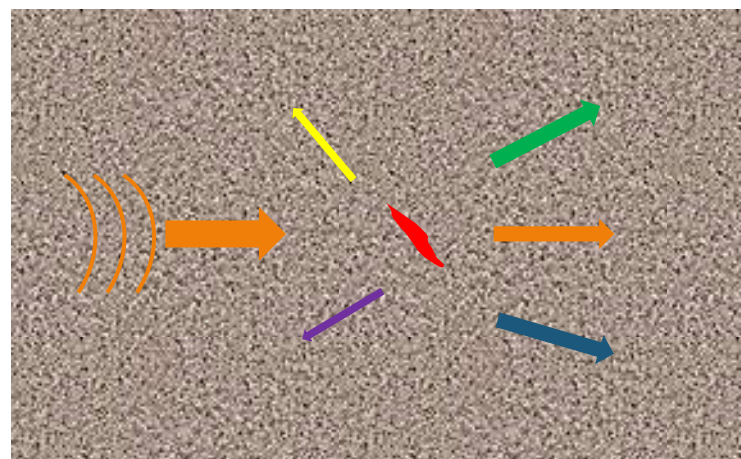
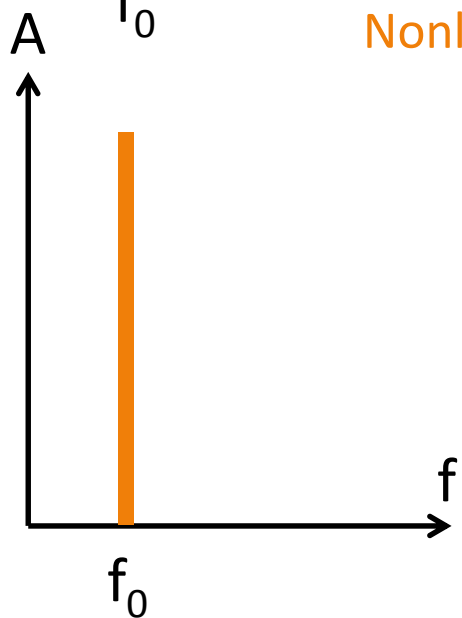
- Micro-damages and changes in constitutive parameters (elastic moduli, sound speed) are **too sensitive** to be detected by linear ultrasonic techniques

Need for Nonlinear Ultrasonic NDE Methods

Linear Acoustic/Ultrasonic NDE Methods

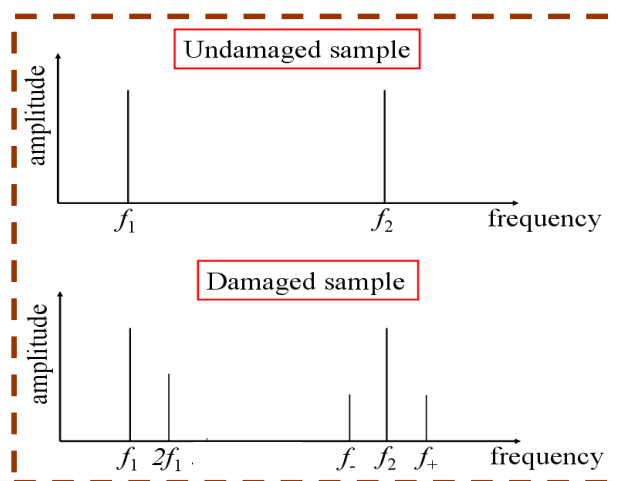


Nonlinear Acoustic/Ultrasonic NDE Methods



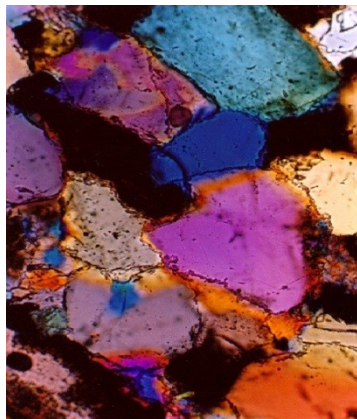
Material Anharmonic Effects

- Materials such as aluminium steel, glasses, single crystals and numerous others exhibits *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**)

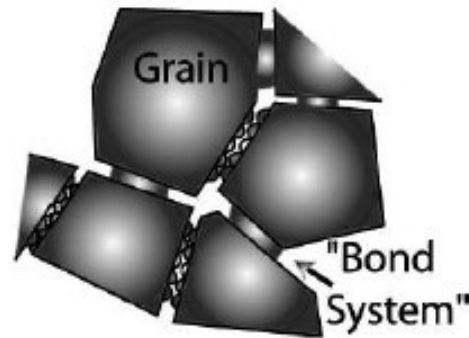


Material Hysteretic Effects

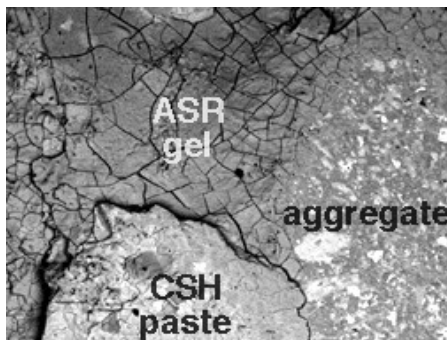
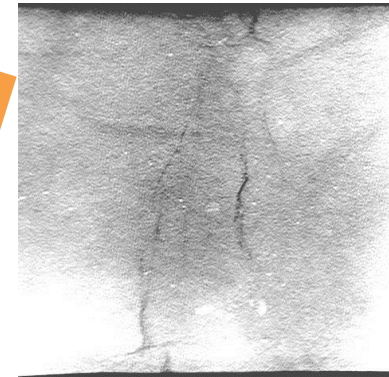
- Materials such as rock, soil, ceramics, concrete, but also damaged composite and metal structures manifest *biphasic nature* (hard grains and soft bond systems), i.e. micro-damage zones with *hysteretic nonlinearity* (**non-classical nonlinear theory, NME**)
- Physical dynamic models attribute this 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**



Sandstone

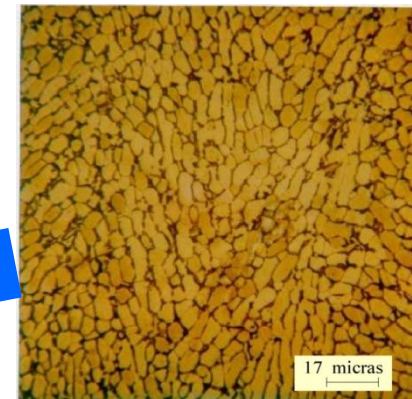


Slate

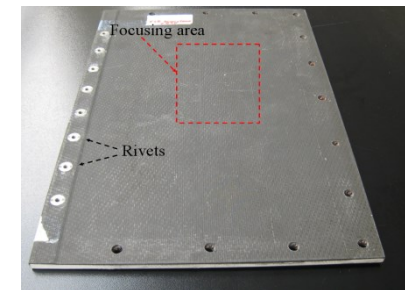
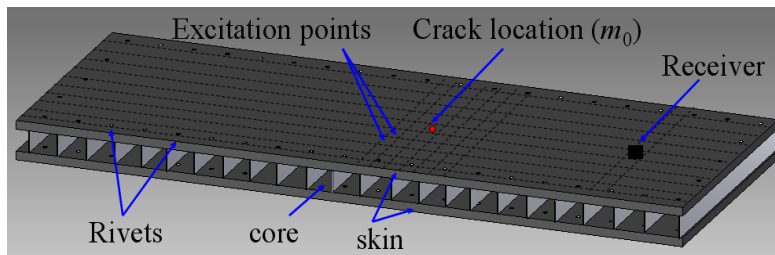


Concrete

Some Alloys

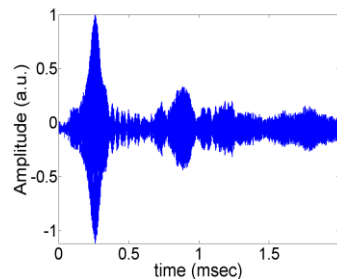


Nonlinear NDE Ultrasonic Imaging Method

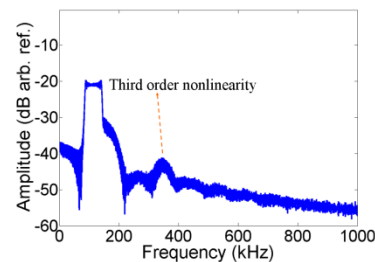


Damaged zone “focusing area” divided in a grid of $M=7 \times 6$ “excitation points”

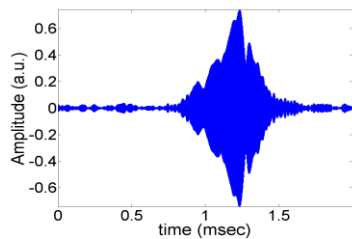
- Third order nonlinear response using **Phase Symmetry Analysis (PSA)** with **chirp** excitation and **Inverse Filtering (IF)**⁵



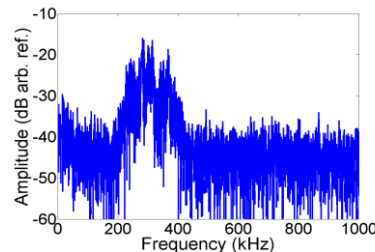
FFT



Measured Signal



FFT

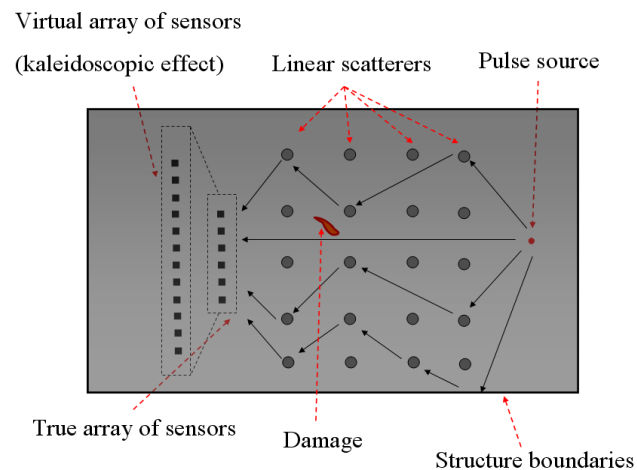
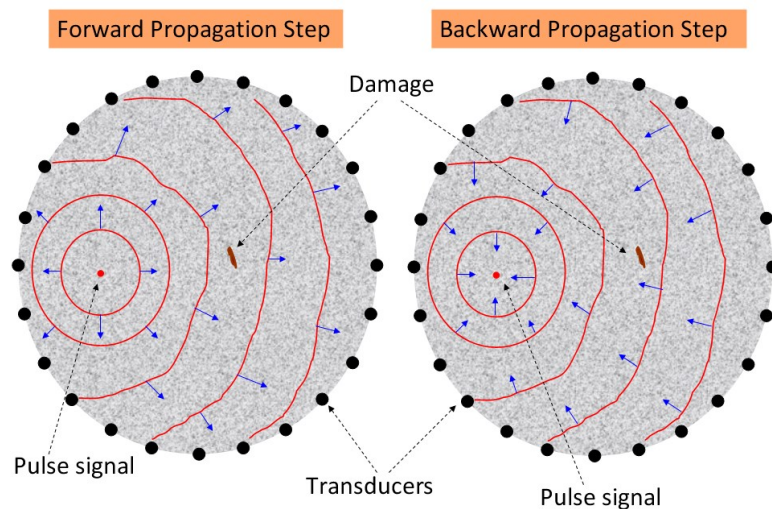


Third Order Response
with PSA

⁵Ciampa, 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

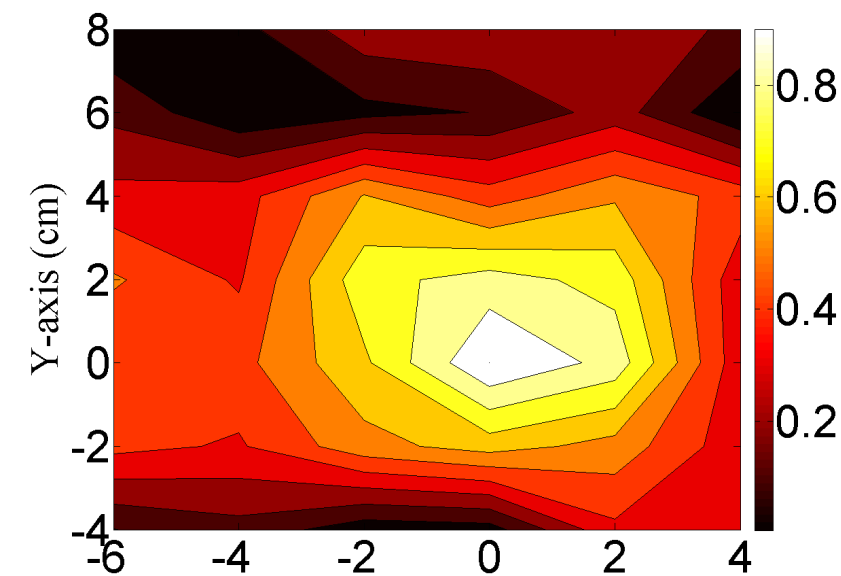


- The *reverberant diffuse wave field* (boundary reflections, mode conversion) in a geometrically complex medium enhances the spatial focusing of the re-emitted signals (*Kaleidoscopic effect*)
- Only **one receiver sensor** can be used for optimal refocusing

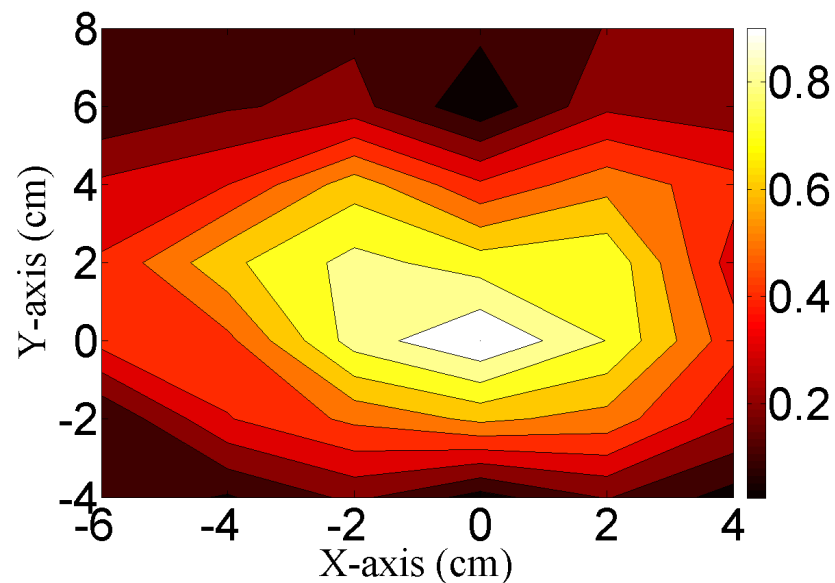
Nonlinear Third Order Imaging Results

Receiver and damage coordinates

	X-coordinates [cm]	Y-coordinates [cm]
Receiver position (case T1)	60	17
Receiver position (case T2)	4	22
Damage location	38	24

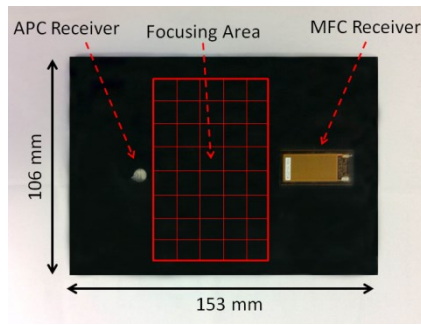



Case T1



Case T2

Nonlinear Second Order Imaging Method



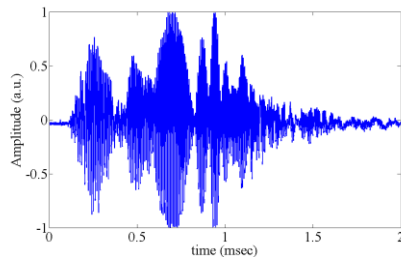
C-Scan




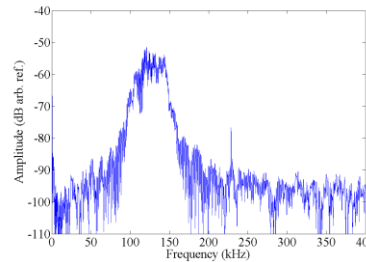
- CFRP
- 153 x 106 x 3 mm
- $[0/45/90/-45]_s$
- BVID @ 10 J

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

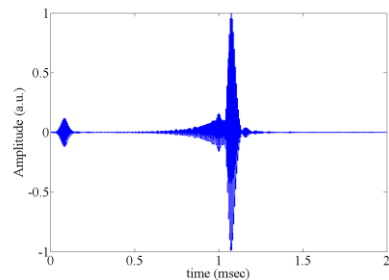
- Second order Nonlinear Response using Phase Symmetry Analysis



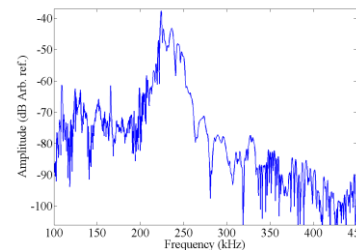
FFT

Measured Signal



FFT

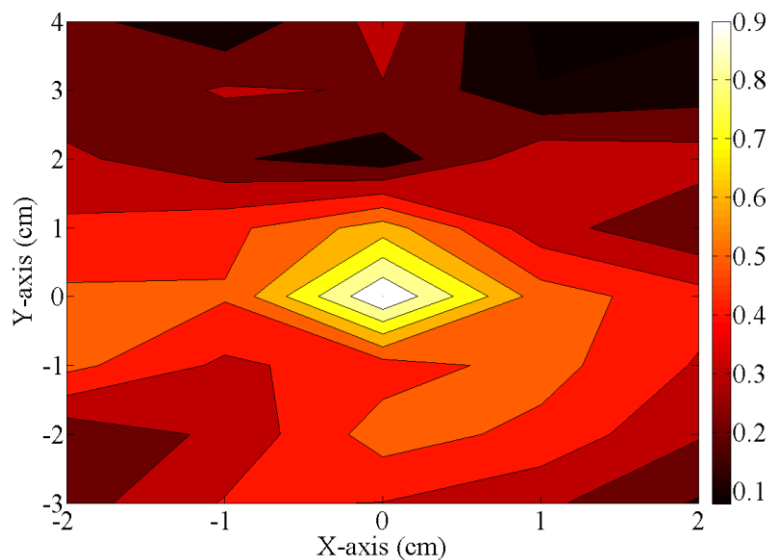



Second Order Response
 with PSA

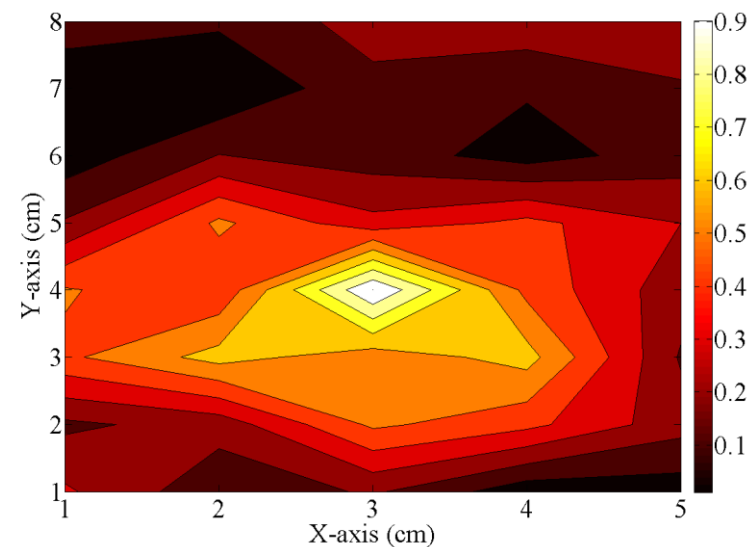
Nonlinear Second Order Imaging Results

Receiver and damage coordinates

	X-coordinates [mm]	Y-coordinates [mm]
APC sensor (case S1)	30	50
MFC sensor (case S2)	90	48
Damage location	59	53



Case S1

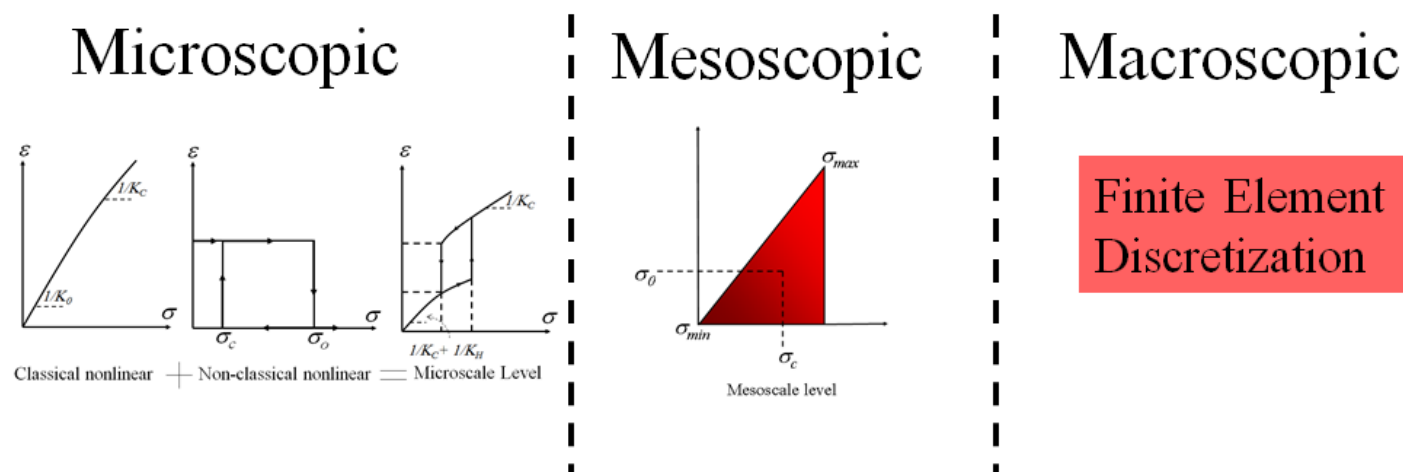


Case S2

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

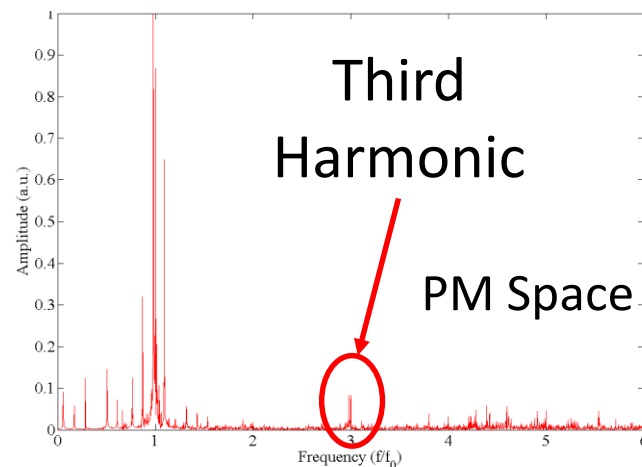
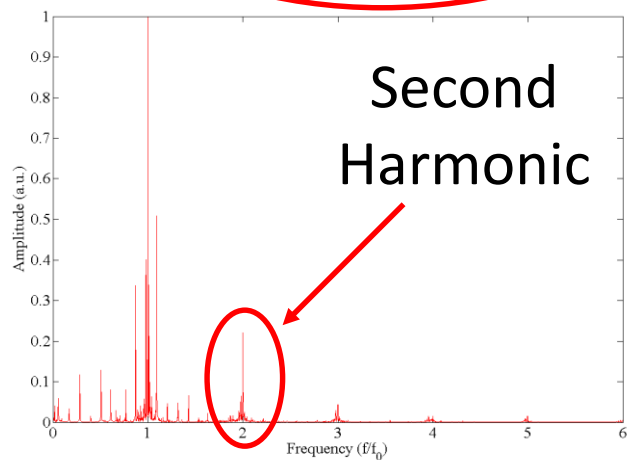
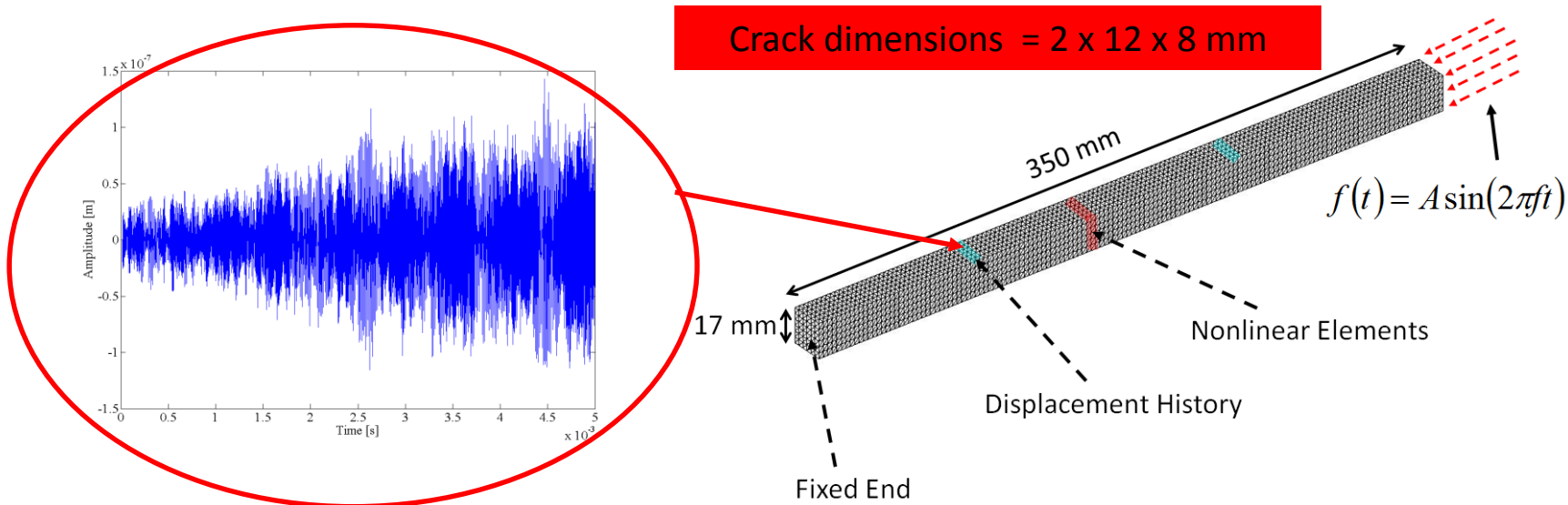
In the Multiscale model, intermediate (**mesoscopic**) material elements are introduced between the **microscopic** mechanics (micro-cracks, grain size, etc...) and the **macroscopic** structural behaviour



- 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

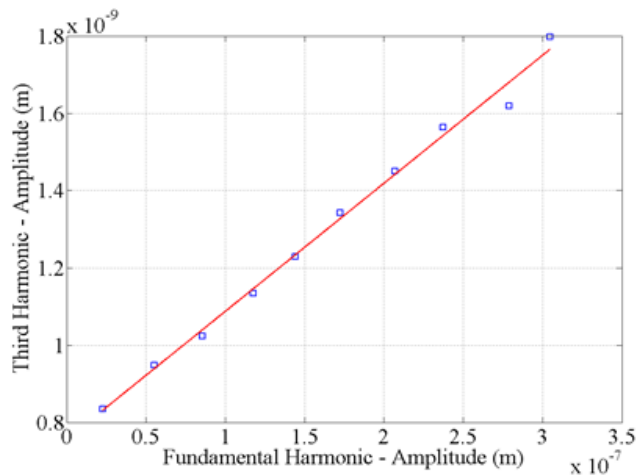
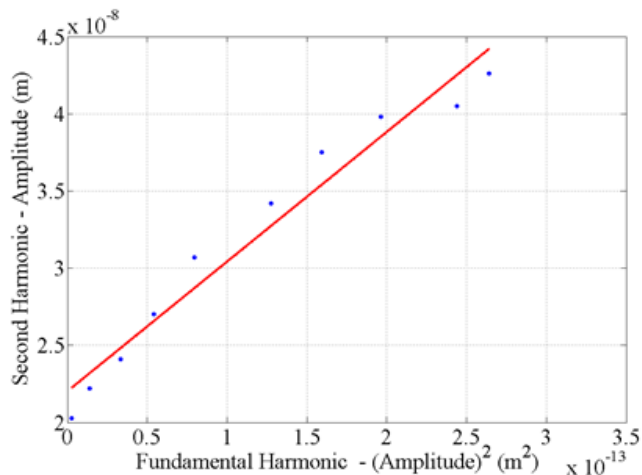
Numerical Results – Composite Bar

3D Numerical Results for a composite bar with in-plane harmonic wave propagation ($f_0 = 100$ kHz)

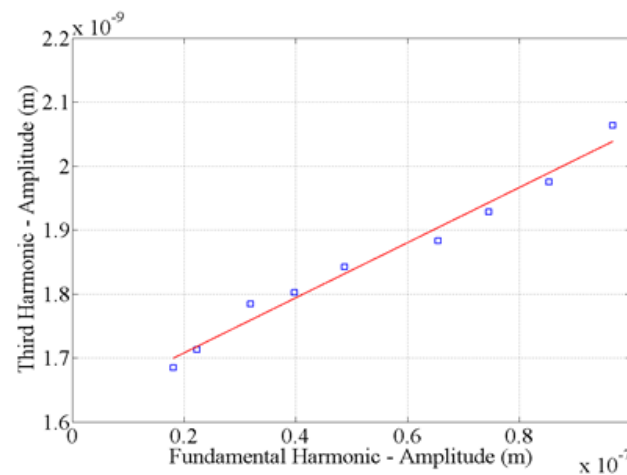
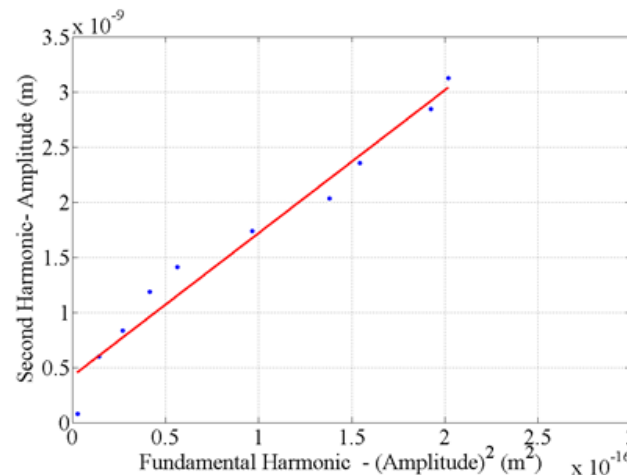


Numerical Results – Isotropic and Composite Bar

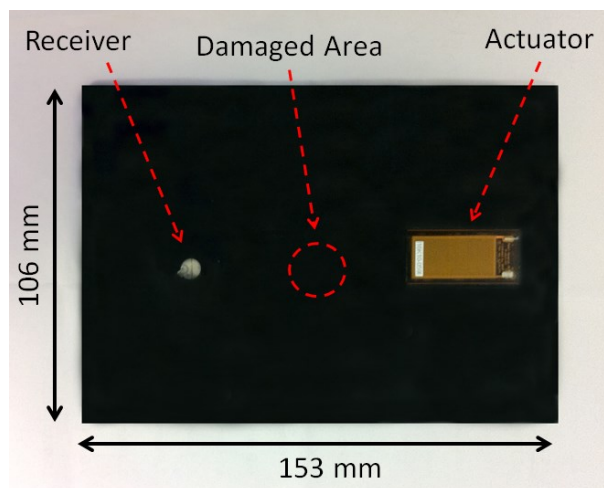
Isotropic



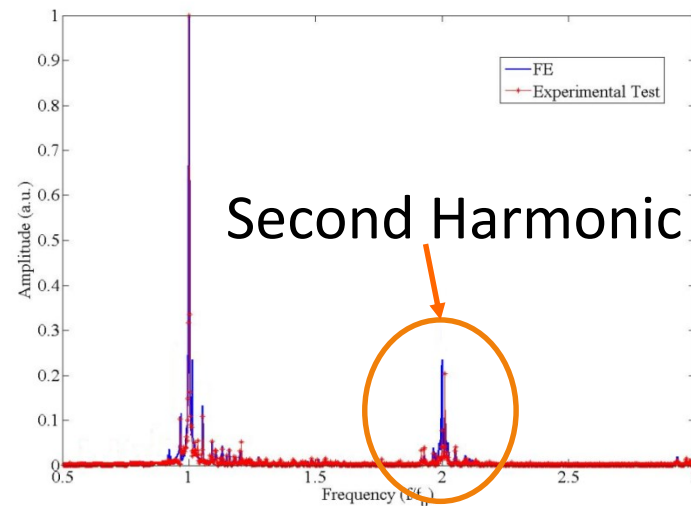
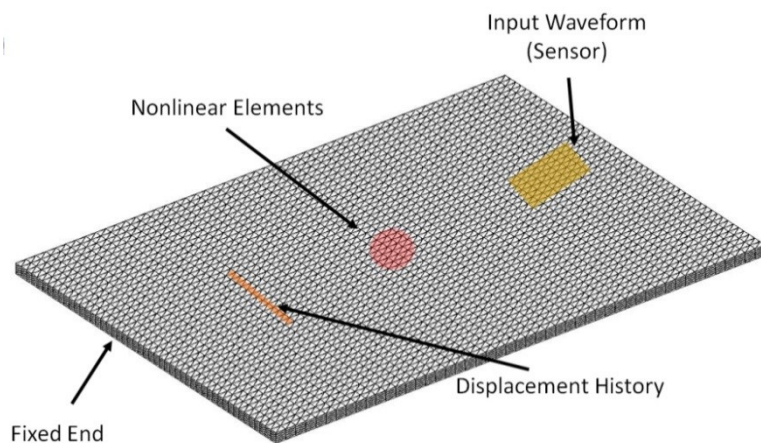
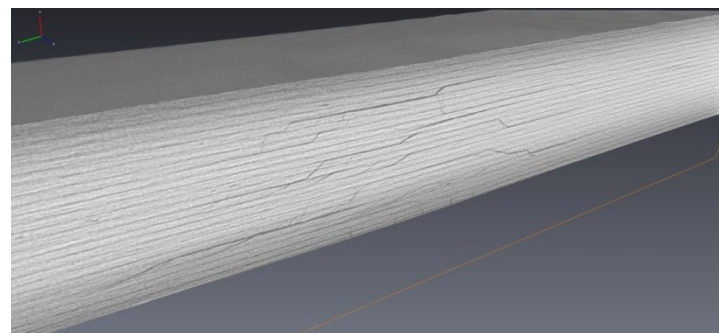
Composite



Numerical and Experimental Results – Composite Panel



X-Ray Tomography



For Further information:

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Thank you for your attention!!