Structural Health & Condition Monitoring

A brief introduction

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Motivation for Monitoring

Safety

"Design rules for aircrafts are written in blood" – lessons learned have set design rules for structural parts in aircrafts, but also raised the desire to know what is going on (or has been going on) in an aircraft

Optimisation Operational Cost

The evolution from calender based maintenance to condition based maintenance – "Just–in-time" maintenance – relies on the development of understanding the physics of damage *and* the ability to monitor the damage features

Motivation for Monitoring – *continued*

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Life expectancy & safe extension

Optimising the use of components of a structure relies on knowledge of the loading history and/or the current structural state of the system

Motivation for Monitoring – *continued*

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Life expectancy & safe extension

Optimising the use of components of a structure relies on knowledge of the loading history and/or the current structural state of the system

Concluding:

- Cost driven, increasing efficiency (robustness, reliability) of systems
- Safety driven, increasing reliability (robustness) of systems
- Smart use of resources, limiting waist and energy consumption (efficiency)

Monitoring Process

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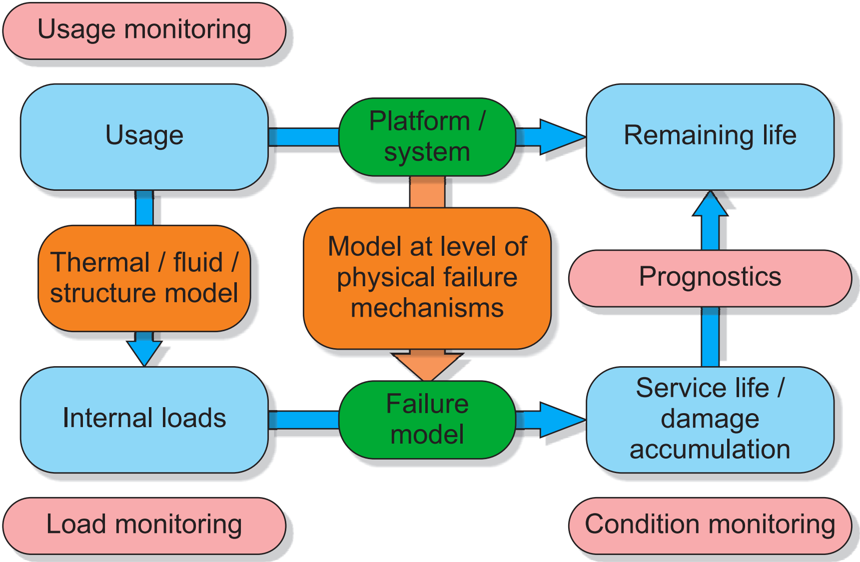

Monitoring Types

Use based Monitoring

Measuring the times a system is used

- Uncorrelated, random use
- Correlated use, e.g. number of cycles

Load based Monitoring

Measuring the loads/load levels on a structure

- Forces/Moments
- Accelerations
- Vibration levels

Monitoring Types

Structural Health & Condition Monitoring

Measuring the current capability of a structure or system to fulfill its intended function

- Strain measurements
- Damage detection
- Degradation measurement
- ...

Monitoring Process

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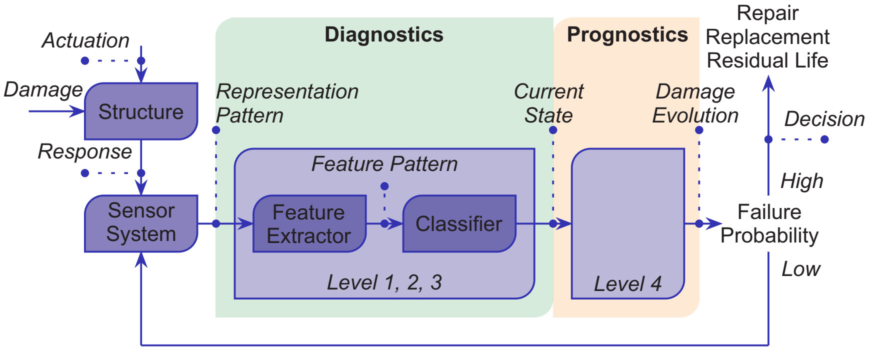

Feature Damage sensitive parameter

Classifier Quantitative number indicating the current condition

Ooijevaar, T.H. (2014) *Vibration based structural health monitoring of composite skin-stiffener structures*. PhD-Thesis, University of Twente. ISBN 978-90-365-3624-0

Diagnostics & Prognostics

Diagnostics

Estimate current state of the structure, four stage process:

1. Operational evaluation
2. Data acquisition
3. Feature extraction
4. Classification

Prognostics

Estimate remaining life time, using

- Damage evolution models
- Past experience

Performance

Performance levels

1. Verification of presence
2. Determination of location
3. Estimation of extent/severity
4. Prediction of remaining service life

Local versus global methods

Global Complete structure, limited in sensitivity

Local Focus on part of structure, prior knowledge damage critical locations required – Hot spot monitoring

EU FP7 SARISTU Smart Intelligent Aircraft Structures

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Objectives (amongst others, see www.saristu.eu):

- Limit the integration cost of Structural Health Monitoring (SHM) systems
- In-service inspection cost reductions of up to 1%

Project

- 64 partners, 16 countries *if I counted correctly...*
- 11 Application Scenario, 2 Integration Scenarios (full scale demonstrators: wing and door surrounding)

Application Scenario 06, Impact damage assessment using integrated ultrasonic sensors

- NDI Inspection of door surrounding structure using guided waves
- Tool for damage assessment

Objective

Development of a GUI-based tool to assess impact damage in a composite structure

Tool

MATLAB© based

Impact damage

Delamination of ∼30 mm diameter;
Barely Visible Impact Damage (BVID)

Composite structure

Full scale door surrounding

Door Surrounding Structure

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Door Surrounding Structure

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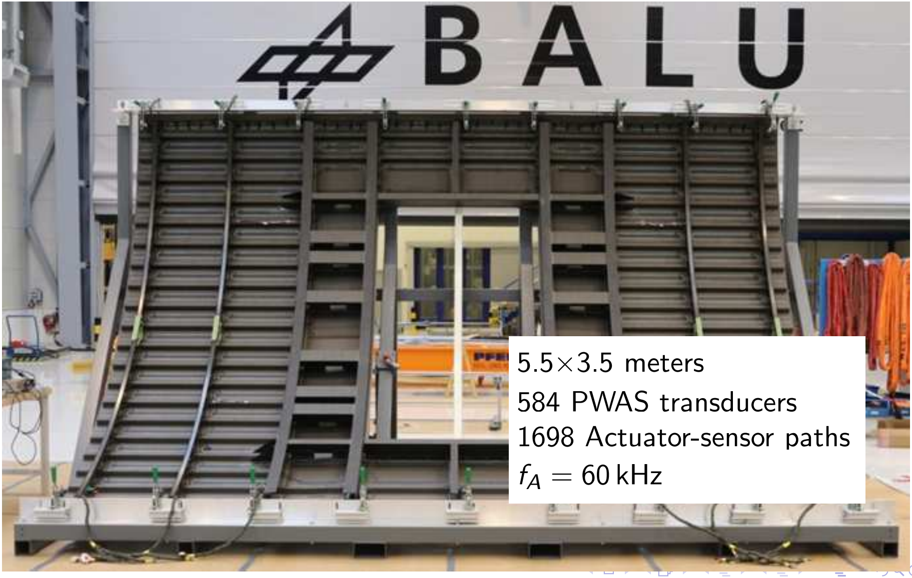

5.5×3.5 meters

584 PWAS transducers

1698 Actuator-sensor paths

$f_A = 60\,\text{kHz}$

Introduction to Sensors

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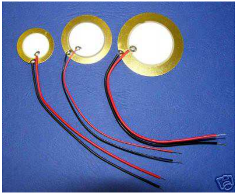
- Accelerometer
- Force transducer
- Laser-vibrometer
- Strain gauges
- Piezo-electric sensor
- Optical fibre
- MEMS

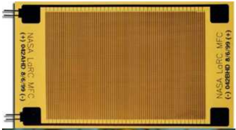
Sensors & Monitoring

Suitability for SHM or CM depends on level of integration of the sensor in the structure!

Piezo-electric sensor

- Strain measurement
- High level of integration
- Low cost, inversely proportional to accuracy
- High frequency range
- Sensor, actuator and energy harvester
- Low strain, no resistance to tensile strain
- Macro Fibre Composites: high level of flexibility
- Sensitive to fatigue
- Extensive wiring (can be embedded)

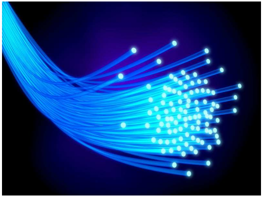




http://www.ndk.com/en/sensor/ultrasonic/basic02.html

http://icb.nasa.gov/archive/2006

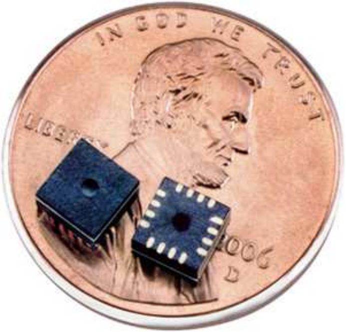
Optical Fibres



- Reflection and refraction of light
- Fibre bragg grating
- Strain measurement
  - Extreme accuracy possible for static strains
  - Lower performance for dynamics strains
- Temperature dependency
- Multiplexing, single wire with multiple sensors
- Light source / expensive data acquisition

Micro Electronic Mechanical Systems

- Typical size 1–100µm
- High level of integration
- Limited ranges
- Limited signal strength
- Low power usage
- Various types of sensors
  - piezo-electric
  - accelerometer
  - gyroscope
  - microphones
  - *etc.*...



Piezo-electric Wafer Active Sensors

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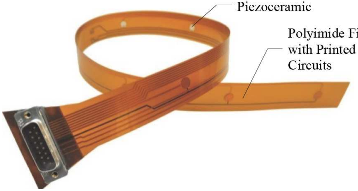

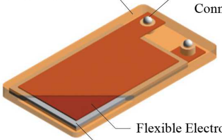

- Piezo-electric diaphragm
- PI151/155/255: low cost
- Embedded in structure, e.g. via co-bonding
- Available as film

D. Schmidt, A. Kolbe, P. Wierach, S. Linke, S. Steeger, F. v. Dungern, J. Tauchner, C. Brue and B. Newman, Development of a door surrounding structure with integrated structural health monitoring system. In *Smart Intelligent Aircraft Structures (SARISTU) – Proceedings of the Final Project Conference*, Ed. P.-C. Woelcken, M. Papadopoulos, Springer 2015, p935-945

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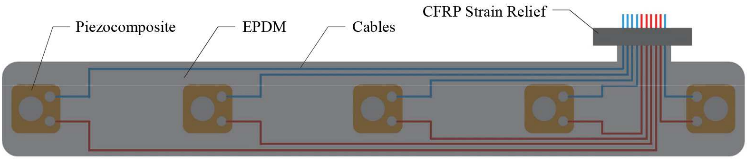

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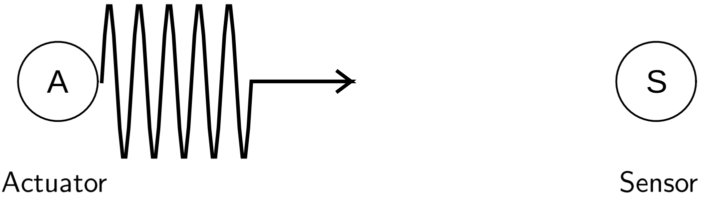
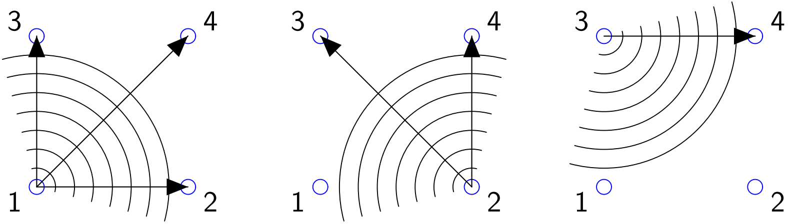
Principle of Acousto-Ultrasonics



- High frequency wave packet sent by actuator
- Guided waves: $f \sim\in \langle 50, 500\rangle$ kHz
- Wave traveling in radial direction in homogeneous material
- Signal received by sensor
- Damage alters signal received

RAPID

Reconstruction Algorithm for Probabilistic Inspection of Defects



Paths:

- 1 – 2
- 1 – 3
- 1 – 4

Paths:

- 2 – 3
- 2 – 4

Paths:

- 3 – 4

Each path covered only in single direction: assumption of reciprocity ($i \rightarrow j \equiv j \rightarrow i$)

Probability Distribution Function

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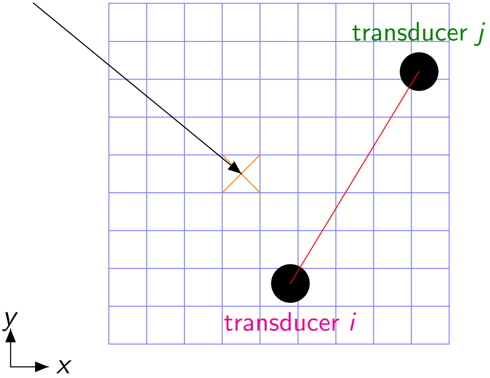
Actuator/Sensor path k

transducer i to transducer j

Damage intensity $I(x, y)$



$$I(x, y) = \sum_{k=1}^{N_p} (1 - \rho_k) \left(\frac{\beta - R(x, y)}{\beta - 1} \right)$$

Correlation coefficient ρ_k

- 1: no damage
- <1: damage

Damage coefficient d_k

- 0: no damage
- >0: damage

$$\rho_k = \frac{1}{d_k + 1}; \; d = \frac{1}{\rho_k} + 1$$

Probability distribution function

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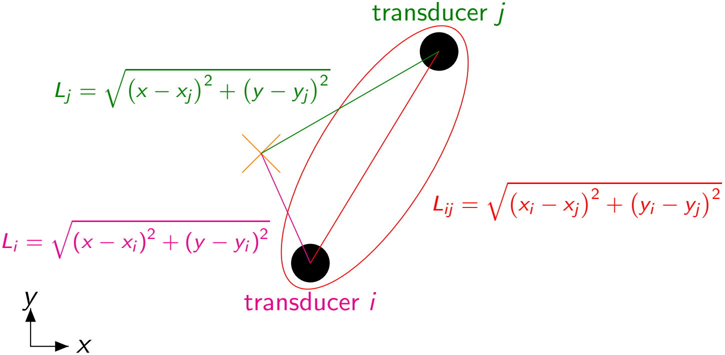
Actuator/Sensor path k

transducer i to transducer j

$$R(x,y) = \begin{cases} \frac{L_i + L_j}{L_{ij}} & \text{if } R(x,y) < \beta \\ \beta & \text{if } R(x,y) \geq \beta \end{cases}$$

β size parameter ellipse



Damage Identification Algorithms

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Method Name	Abbr.	Mathematical Formula
Correlation Coefficient	CC	$\rho = \frac{\sum_{i=1}^{N}(s_{H,i}s_{D,i}) - \sum_{i=1}^{N}(s_{H,i})\sum_{i=1}^{N}(s_{D,i})}{\sqrt{\sum_{i=1}^{N}(s_{H,i}^2) - \left(\sum_{i=1}^{N}(s_{H,i})\right)^2}\sqrt{\sum_{i=1}^{N}(s_{D,i}^2) - \left(\sum_{i=1}^{N}(s_{D,i})\right)^2}}$
Signal Amplitude Peak Ratio	SAPR	$DI = \frac{\max(S_H)}{\max(S_D)}$
Signal Amplitude Peak Squared % Differences	SAPS	$DI = \left(\frac{\max(S_H) - \max(S_D)}{\max(S_H)}\right)^2$
Signal Sum of Squared Differences	SSSD	$DI = \frac{\sum_{i=1}^{N}\left[(s_{H,i} - s_{D,i})^2\right]}{\sum_{i=1}^{N}\left[s_{H,i}^2\right]}$
Discrete Wavelet Transform	DWT	$DI = \frac{\sum_{i=1}^{N}\left[(\boldsymbol{DWT}(s_{H,i}) - \boldsymbol{DWT}(s_{D,i}))^2\right]}{\sum_{i=1}^{N}\left[(\boldsymbol{DWT}(s_{H,i}))^2\right]}$
Ratio of Covariance Matrix Eigenvalues	RCME	$\rho = 1 - \frac{\lambda_2}{\lambda_1}$

Assessment with Graphical Interface

Objectives:

- Analysis of on the fly data: Inspection
- Investigation on data: Development of inspection

Assessment with Graphical Interface

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- Ability to assess the structure with complex technologies, but without in-depth knowledge of these technologies
- Ability to develop insight in damages in composite structure, accuracy of technologies

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Richard Loendersloot, Inka Buethe, Pavlos Michaelides, Maria Moix-Bonet and George Lampeas, Damage Identification in Composite PanelsMethodologies and Visualisation. In *Smart Intelligent Aircraft Structures (SARISTU) – Proceedings of the Final Project Conference*, Ed. P.-C. Woelcken, M. Papadopoulos, Springer 2015, p581-606

Assessment with Graphical Interface

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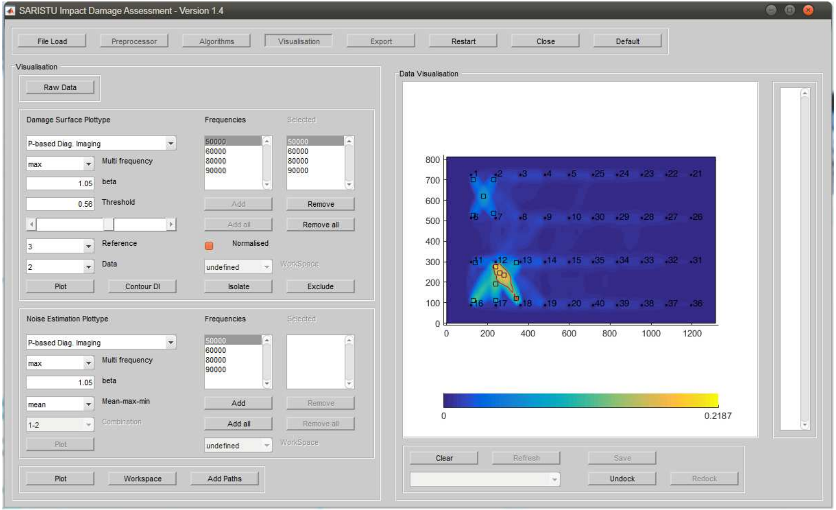

Assessment with Graphical Interface

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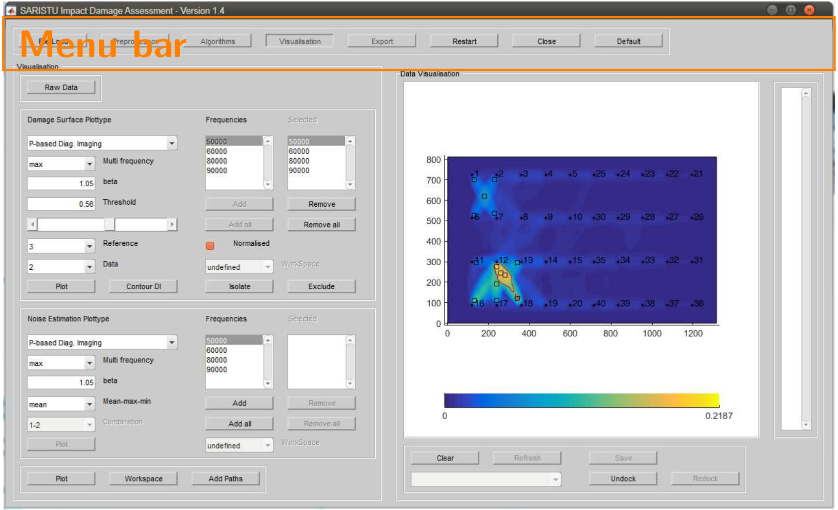

Assessment with Graphical Interface

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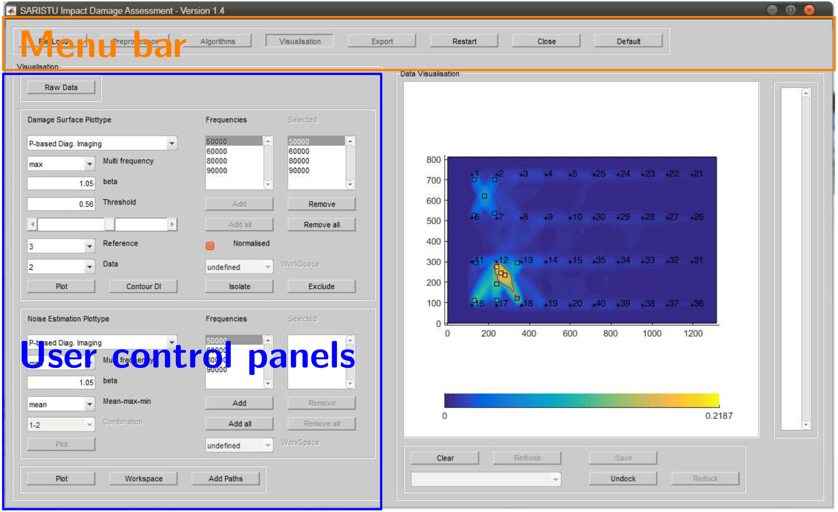

Assessment with Graphical Interface

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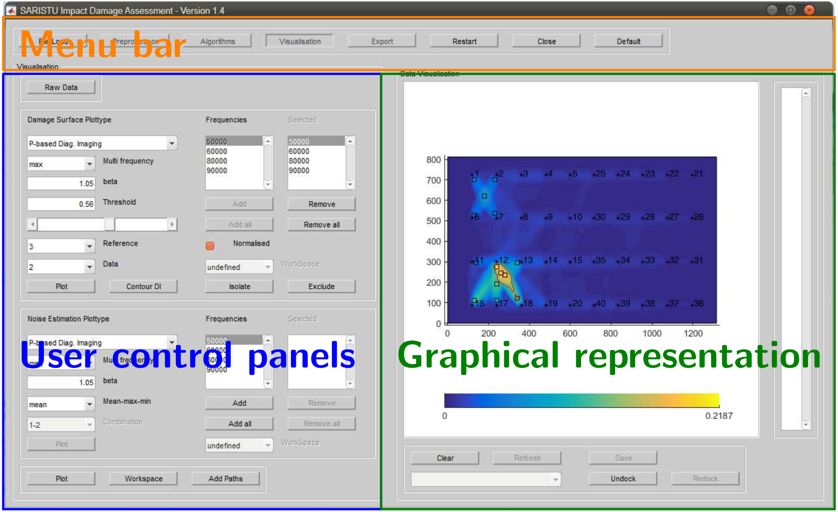

Visualisation

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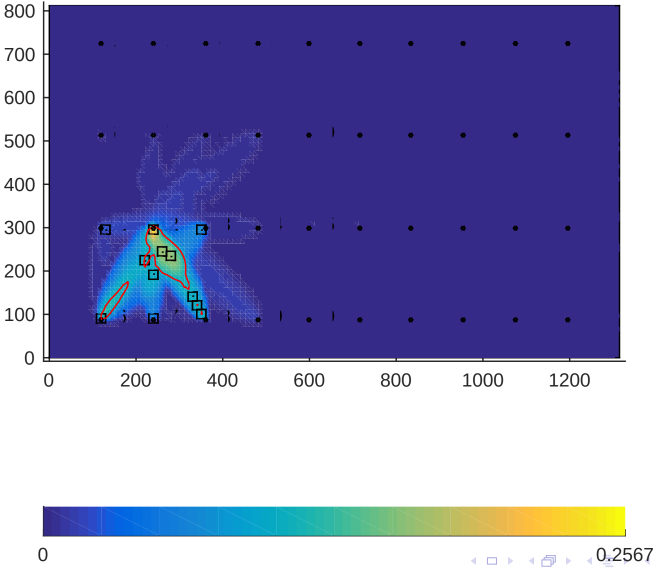

Discussion

	I_{thrs} [%]	x [mm]	y [mm]	A [mm^2]
NDI		835	618	574.06
A_0 mode	95	833.2	621.5	586.9
S_0 mode	94	833.2	531.3	25.1

Maria Moix-Bonet, Benjamin Eckstein, Richard Loendersloot and Peter Wierach, *Identification of barely visible impact damages on a stiffened composite panel with a probability-based approach*, IWHSM-2015, Stanford, USA
Maria Moix-Bonet, Peter Wierach, Richard Loendersloot and Martin Bach, Damage Assessment in Composite Structures Based on Acousto-UltrasonicsEvaluation of Performance. In *Smart Intelligent Aircraft Structures (SARISTU) – Proceedings of the Final Project Conference*, Ed. P.-C. Woelcken, M. Papadopoulos, Springer 2015, p619-632

Applications of Monitoring

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Aerospace Composite structures, bonded elements, delamination identification. (FP7 SARISTU, NLR)

Wind Turbine Composite (blade) structures, support structures, gears, bearings. (TKI Wind op Zee - SLOWIND & WiMOS)

Water Distribution Inline inspection of AC and PVC pipelines using ultrasound and development of smart pipes with embedded sensors (Wetsus – Centre of Excellence for Sustainable Water Technology - 2 projects)

Railinfra Monitoring of rail assets: rails and switches, wear and damage (Strukton)

Infrastructure Monitoring of bridges (road/rail, concrete/steel), condition assessment and life time expectance (FP7 DestinationRail)

Conclusions and Outlook

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- Monitoring offers insight in what happens with structure or system
- Field of application is broad
- Often high-technology required, but many solutions highly matured

- Relevance of monitoring for future applications high
- Many fields yet unexplored; impact of monitoring can be much higher: "circular economy"

Thank you for you attention
Questions?

Richard Loendersloot

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01.02.2017.