SHM-Systems for Composite Aircraft Structures based on Lambwave Analysis

Research Topics

Michael Sinapius, Daniel Schmidt, Arthur Szewieczek, Peter Wierach, Florian Raddatz, Maria Moix-Monnet, Christoph Heinze

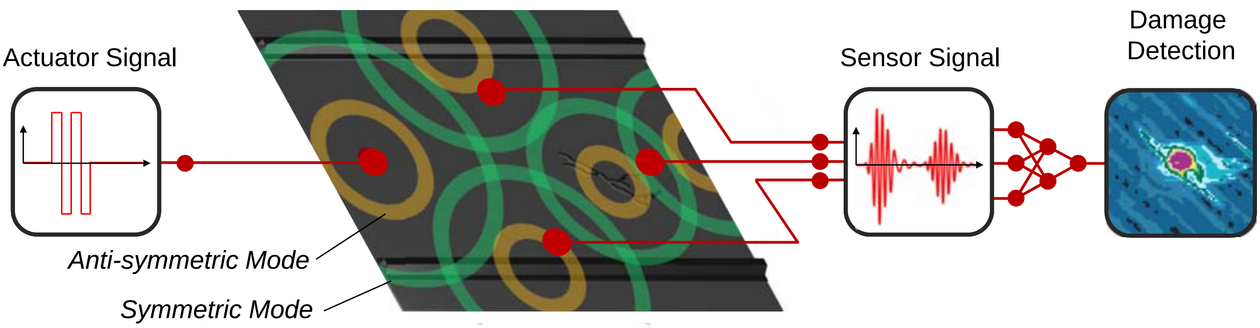
Introduction

- Structural Health Monitoring (SHM) based on Lamb waves is a promising method for in-service inspection of aircraft composite structures
- Lamb waves are highly sensitive to structural damages
- Lamb waves can be excited and received by piezoceramics

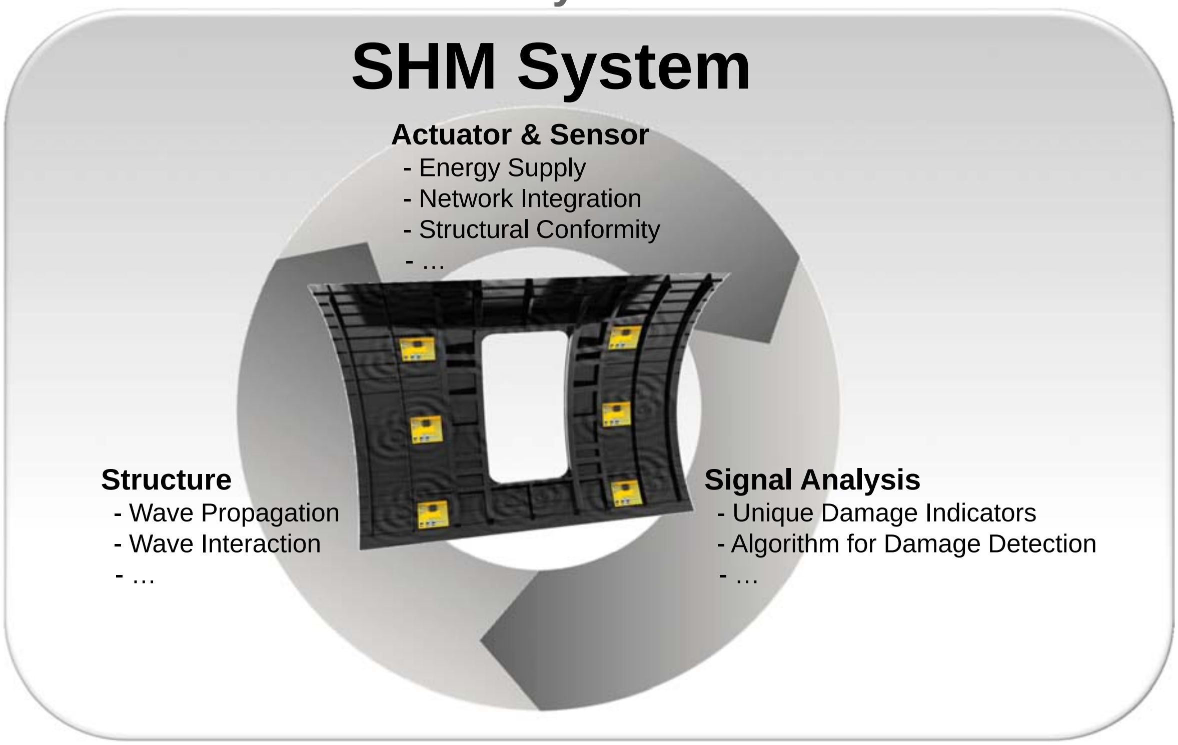
Introduction

Development of SHM network requires:

- Detailed understanding of the propagation of different Lamb wave modes and their individual interaction with damages
- Use of unique indicators for damage detection
- Specific analysis and design with respect to the application scenario



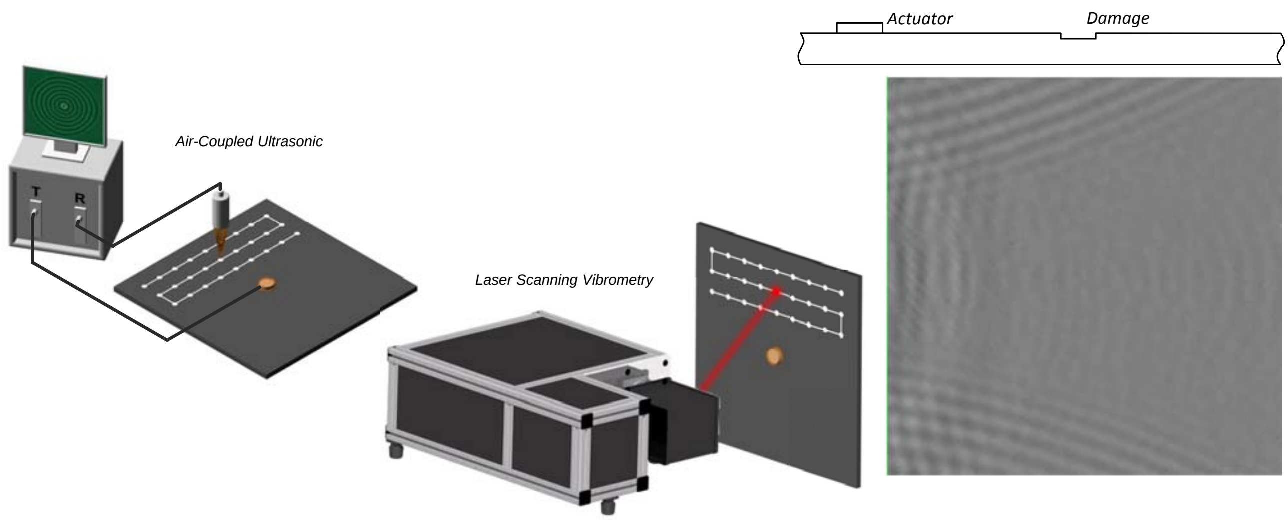
Research fields for SHM Systems



Wave Propagation and Interaction

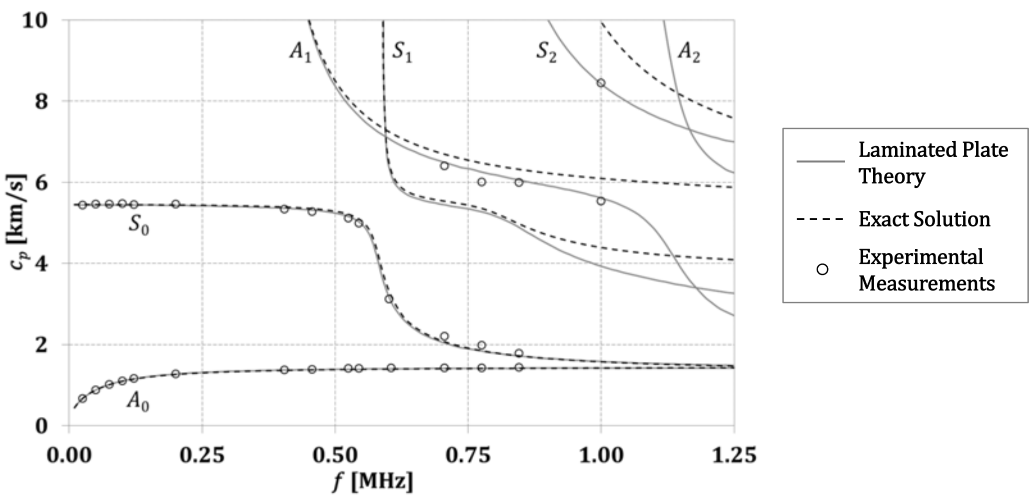
Investigation of the wave propagation and interaction by using:

- Air-coupled ultrasonic techniques
- Laser scanning vibrometry
- Analytical and numerical methods



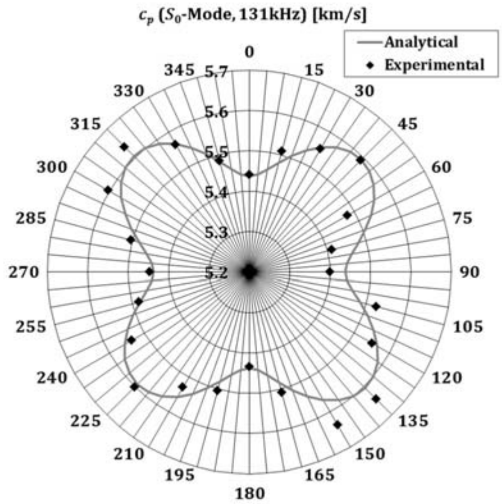
Wave Propagation and Interaction

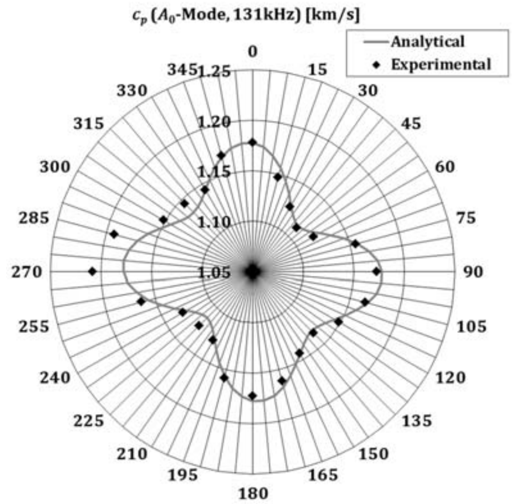
- Dispersion diagram of Lamb waves in CFRP plates
- Comparison of experimental data with theoretical values



Wave Propagation and Interaction

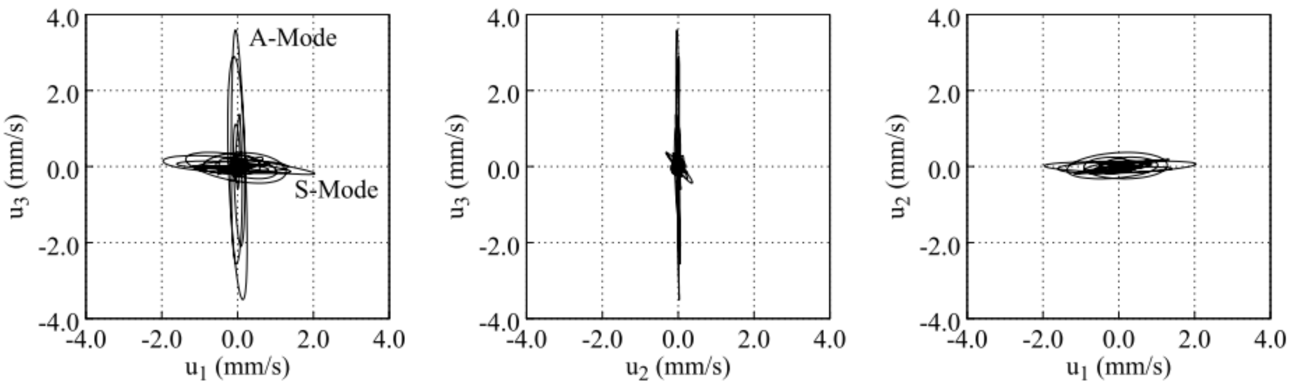
- Measurement and calculation of Lamb wave phase velocities in CFRP plates
- Comparison of experimental data with theoretical values





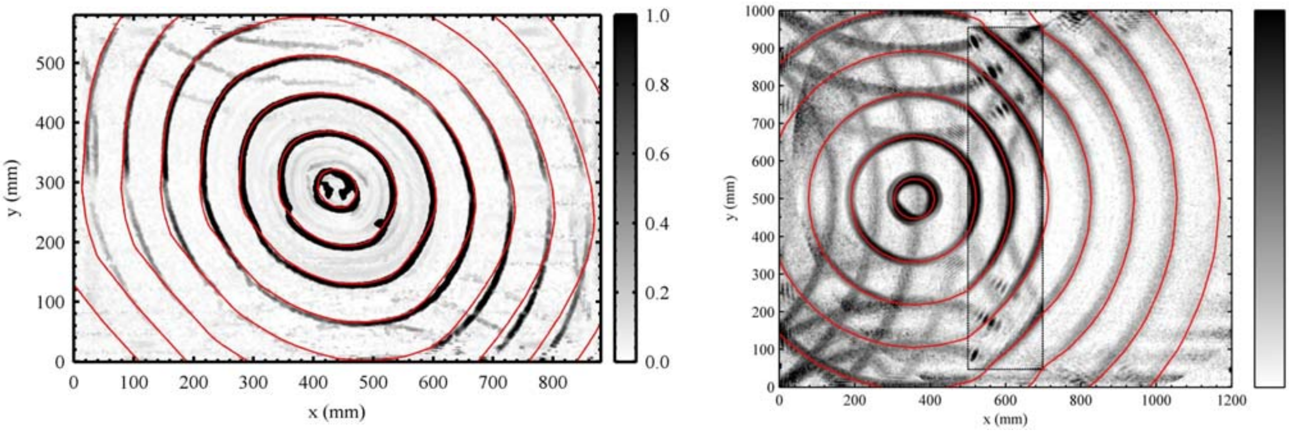
Wave Propagation and Interaction

- Development and operation of a flexible 3D laser vibrometry platform
- Measurement of the in-plane and out-of-plane displacement of each Lamb wave mode



Wave Propagation and Interaction

- Calculation of time-of-flight using directional phase velocities of anisotropic structures
- Iterative time-of-flight calculation of a discretized structure
- Each element shows individual, directional velocity distribution



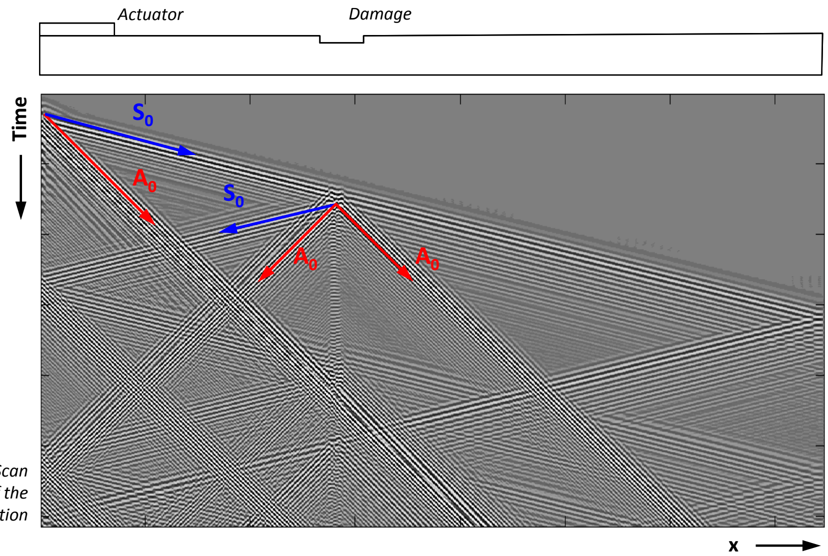
Measurement of wave propagation at different time steps

Calculation of wave propagation at different time steps

Wave Propagation and Interaction

Lamb wave interaction at structural discontinuities like stiffeners, edges, damages, sensors etc.

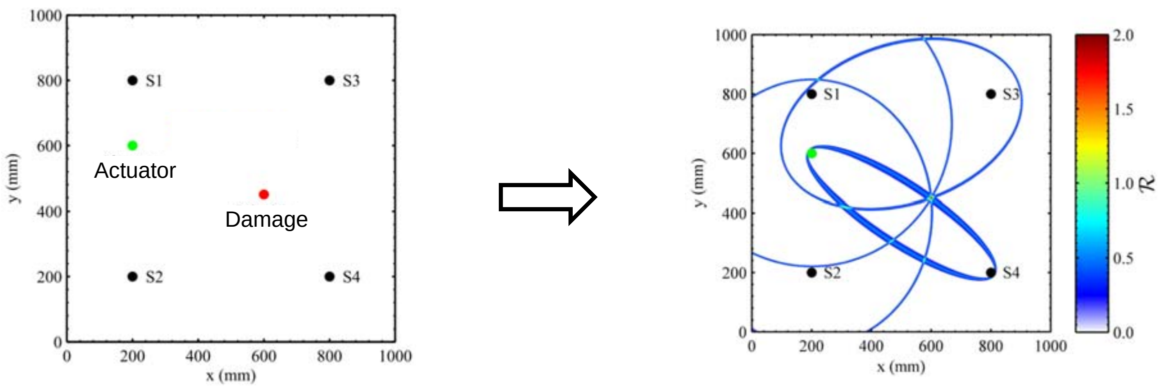
- Reflection, transmission, absorption
- Mode conversion
- Diffraction



B Scan of the Wave Propagation

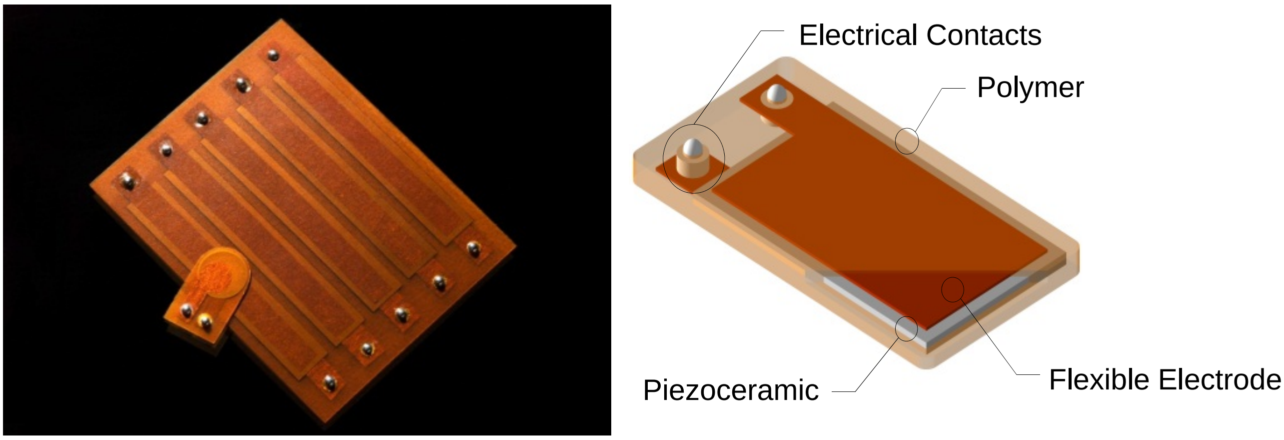
Damage Detection and Localization based on Reconstruction Algorithms

- Determination of local damage probability based on reconstruction algorithms
- Projection and superpositioning of measured signals by using calculated phase velocities
- Very flexible method, which is suitable for complex structures (Compared to triangulations methods)



Actuators and Sensors – Robust SHM Networks

- Piezocomposite Technology:
  - Embedding of brittle piezoceramic plates into a ductile polymer incl. flexible electrodes, electrical contacts and insulation
  - Pre-compression allows to apply tensile/bending load
  - Improved damage tolerance and lifetime
  - Electrical insulation

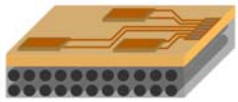


Actuators and Sensors – Robust SHM Networks

- Development of SHM networks in form of semi-finished parts which include piezoceramic transducers, wires and electrical connection
- Integration of the semi-finished parts into the composite manufacturing process (integral manufacturing process, co-bonding)
- Reduction of manufacturing steps (e.g. bonding process, cabling) and costs





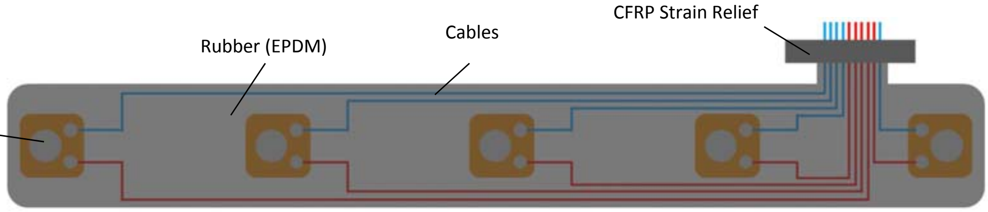


Piezoceramic → Packaging into Polymer → Piezocomposite SHM Network → Composite Semi-finished Parts → Co-bonding Manufacturing Process → Active Composite Structure

Actuators and Sensors – Robust SHM Networks

- Piezocomposites and cables with stranded cores embedded into rubber
- Vulcanization of the rubber during the curing of the composite structure
- Robust SHM array due to the protection of the piezocomposites and cables by the rubber
- SHM array can be manufactured in different shapes with different transducers

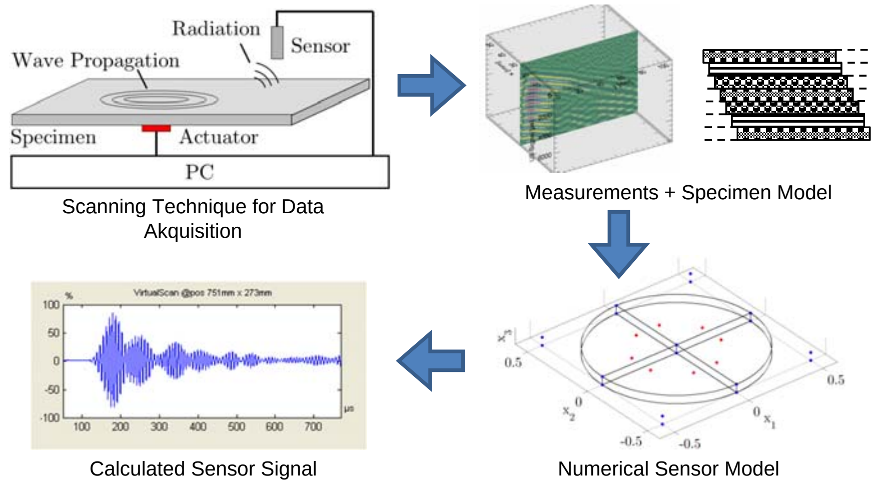
DuraAct



SHM Array based on Piezocomposite Technology

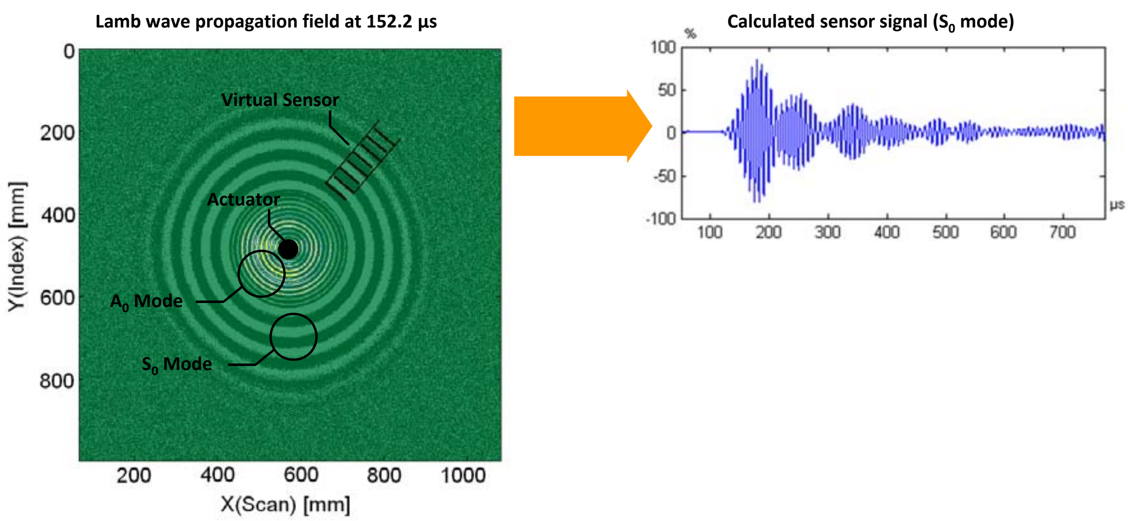
Actuators and Sensors – Virtual Sensors

- Development of "virtual sensors" which allow the design of complete SHM networks by optimizing sensor number, position, form and material properties
- Calculation of sensor signals out of wave propagation measurements acquired by an air-coupled ultrasonic scanning technique



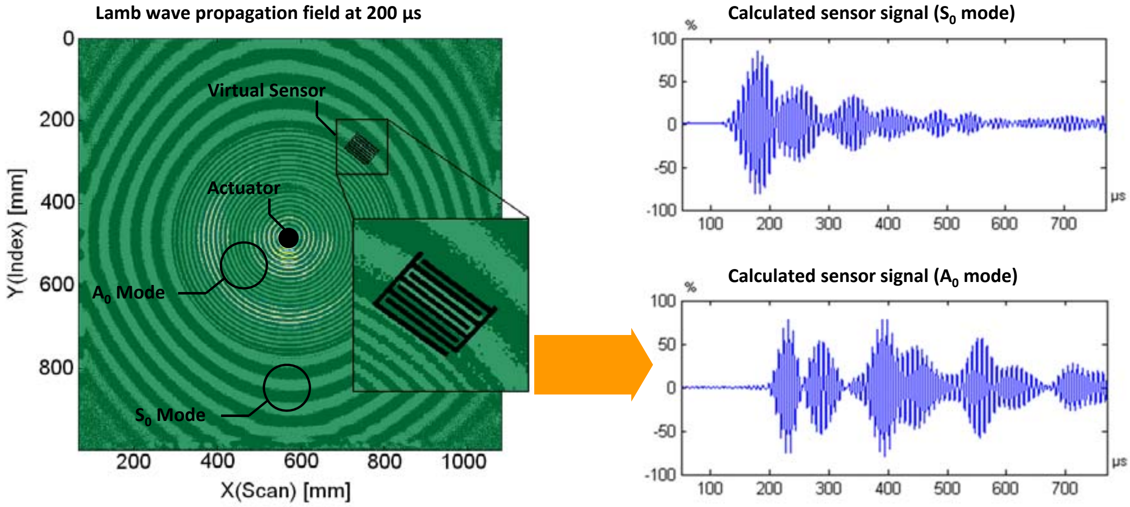
Actuators and Sensors – Virtual Sensors

- Virtual sensor adjusted to the wavelength of the S_0 mode
- Wavelength of S_0 mode: 49 mm



Actuators and Sensors – Virtual Sensors

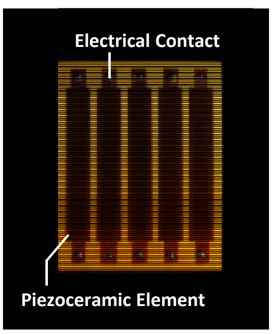
- Virtual sensor adjusted to the wavelength of the A_0 mode
- Wavelength of A_0 mode: 13 mm



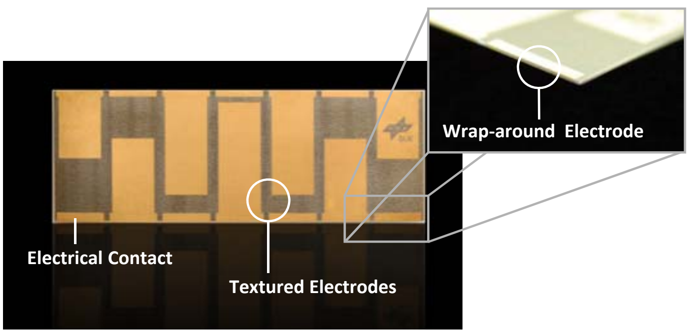
Actuators and Sensors – Mode Selective Transducers

- Development of mode selective transducers in order to:
  - Excitation and receiving of particular Lamb wave modes in CFRP plates
  - Reduce the complexity of Lamb wave propagation fields
- Use of interdigitated electrode design
- Electrode distance correspond to half of wavelength of the desire mode

Piezocomposite

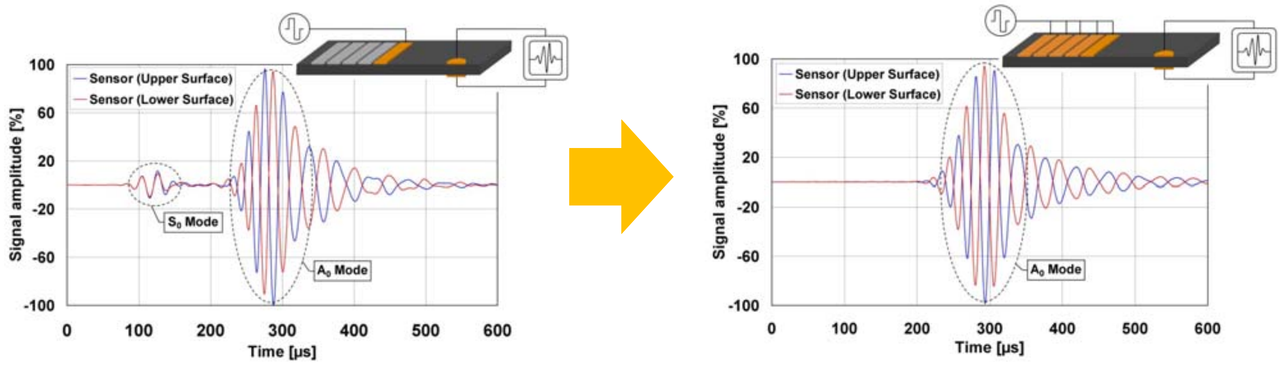


Monolithic Piezoceramic



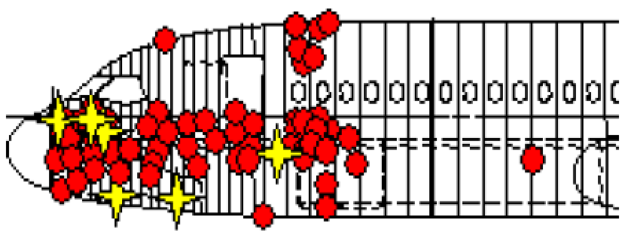
Actuators and Sensors – Mode Selective Transducers

- Development of mode selective transducers in order to:
  - Excitation and receiving of particular Lamb wave modes in CFRP plates
  - Reduce the complexity of Lamb wave propagation fields
- Use of interdigitated electrode design
- Electrode distance correspond to half of wavelength of the desire mode



Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

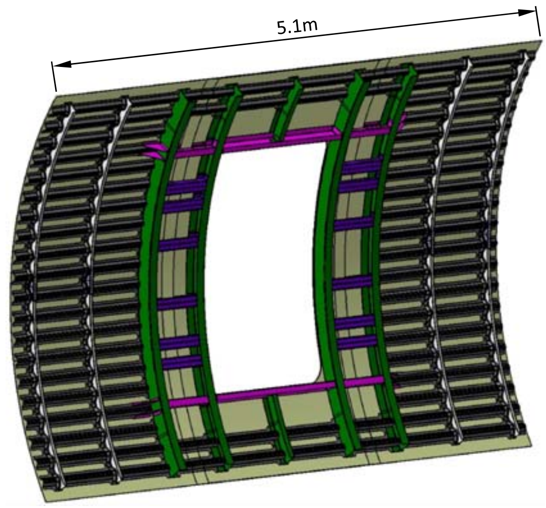
- Development of a door surround structure with SHM network in order to:
  - Integrate complex SHM networks into the manufacturing process of aircraft composite structures
  - Prove of damage detection algorithms in complex, realistic structures
  - High load levels and high concentration of in-service damages



Airbus Operations GmbH

Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

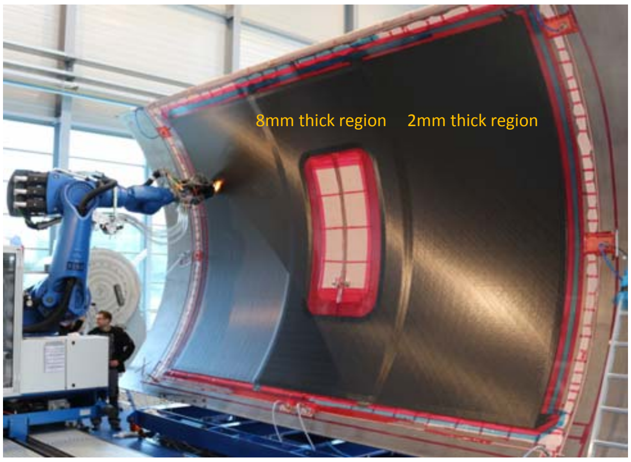
- Full-scale door surround structure made from composite material:
  - Length: 5.1m
  - Width: 3.5m
  - Radius: ~3m
- Integration of 584 piezoceramics
- Representative structural components:
  - Skin with two different thicknesses (2mm & 8mm)
  - 44 stringers
  - 4 normal frames
  - 5 door frames
  - 16 intercostals, 2 sills and 8 brackets



Design of the Door Surround Structure without SHM network

Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

- Skin is made from CFRP prepreg material
- Use of automated fiber placement (AFP) robot
- Layup of two different thicknesses regions (ramp 1:20)

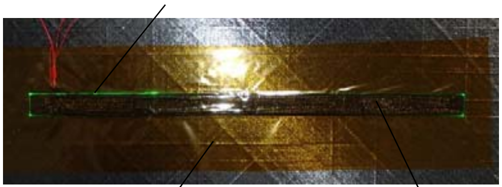


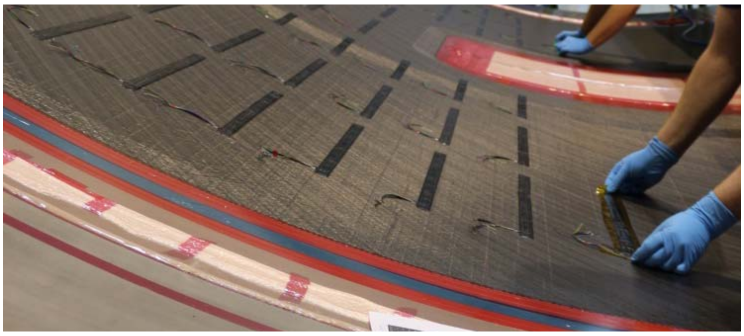
Layup of the Skin Plies

DLR @ Technische Universität Braunschweig

Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

- SHM arrays are applied on a Kapton transfer film
- Transfer film holds the array in shape and simplifies the lay-up
- Application of 126 arrays (584 transducer) on the wet CFRP prepreg
- Laser projection is used to facilitate the positioning of the sensor arrays
- Skin curing process at 180°C and 7bar within the autoclave





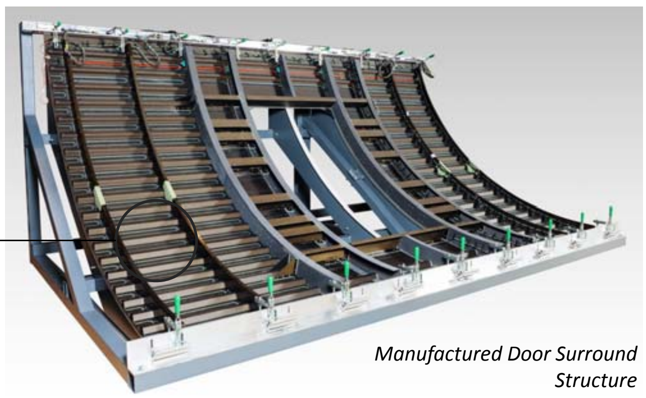
Layup of the SHM Arrays

Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

- Stringer are secondary bonded with film adhesive (150°C, 3bar)
- Frames and sills are assembled with fasteners and shim
- Wiring harnesses with a specific length are pre-fabricated
- Connection between harnesses and transducers by sealed crimp splices
- All 584 piezoceramics survived the manufacturing steps

Sealed Crimp Splices

SHM Arrays

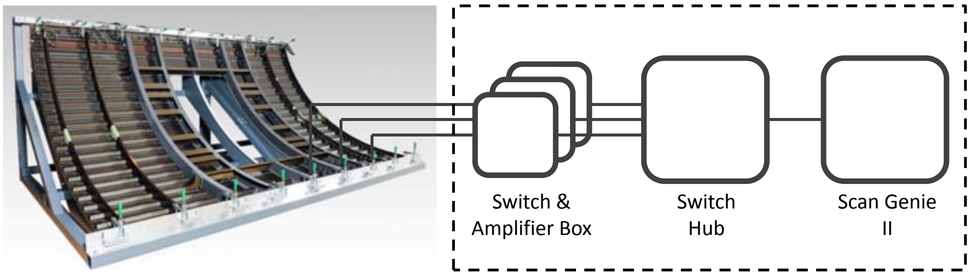


Manufactured Door Surround Structure

Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

- Baseline SHM measurements at different temperatures:
  - Lower frequency range (antisymmetric mode): 50…100kHz
  - Higher frequency range (symmetric mode): 150…250kHz
- Introduction of 112 impacts (<130J) using an impactor gas gun
- Ultrasonic scanning of the impact zone to quantify the damage area
- SHM measurements to detect/locate the damages

Impactor gas gun



Door Surround Structure

Hardware – Acellent Inc.

Manufacturing and Test of Full-scale Door Surround Structure with Integrated SHM Network

- Probability-based diagnostic imaging
- Calculate Damage index for each actuator-sensor pair
- Superposition of damage probability for each pair
- Damage probability indicator → colorbar
- Damage **location** → local maxima
- Damage **size** → threshold on the color scale

Damage Assessment of a stiffened structure

Thank you very much for your attention

Technische Universität Braunschweig