Characterizing the Performance of Lamb Wave Based SHM Systems – A Two-Step Approach Based on Simulation-Supported POD and Reliability Aspects

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Abstract

The performance of conventional NDE systems with one or a few sensors can be adequately described by classical POD concepts. In the case of Lamb wave based structural health monitoring (SHM) the situation is more complex. In SHM a larger number of permanently installed sensors arranged in a network configuration are often used. For this problem the conventional POD concept needs to be adapted since POD becomes a function of position or more general, a function of the specific network configuration. Moreover, the long-term behavior of sensors and electronics plays an important role since their degradation directly affects the POD of the SHM system over time. In the present paper a two-step approach to characterize the performance of Lamb wave based SHM systems based on POD and reliability aspects is presented.

In a first step we introduce a new POD concept for Lamb wave based sensor networks where the effective network aperture is used as a virtual scanning device. Therefore the conventional POD methods already known from classical UT can be directly transferred to SHM. The only exception is the location-dependent POD determined by the specific network configuration. For this purpose a simulation platform is presented that allows the calculation of location-dependent POD values and additionally offers the possibility to optimize the network configuration if the statistical distribution of flaws is empirically known. In a second step we address the age-dependent performance of sensors and electronics by presenting results of an extensive experimental and simulation-supported reliability study on CFRP integrated sensor systems. Environmental tests have been done to investigate the reliability of ultrasonic transducers and electronic components in the longterm. The tested sensor package concept has been specifically designed with respect to functionality (high efficiency of Lamb wave coupling) and reliability of hardware components. We discuss how these aspects can be incorporated in the classical POD framework. As a final result for the description of SHM system reliability we propose a time-dependent or age-related POD, i.e. a POD time curve, rather than a single POD value.

Characterizing the performance of Lamb wave based SHM systems – A two-step approach based on simulation-supported POD and reliability aspects

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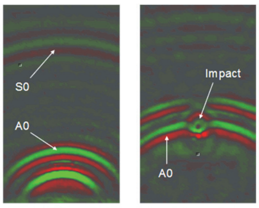
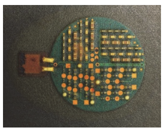
Motivation

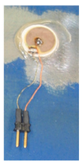
- An emerging trend in modern structure design is the combination of structures and sensors for monitoring purposes (SHM)
- One possible SHM approach is based on guided ultrasonic waves (Lamb waves)



- Sensor nodes typically consist of small piezoelectric transducers and sensor-near electronics for signal processing, power supply and – if possible – wireless communication



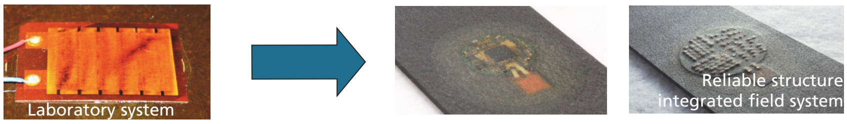
- In the past the sensor nodes were directly attached to the surface of the structure (e.g. by gluing) and electrically connected with cables. This might be sufficient for laboratory measurements but will not be accepted in real aircraft components



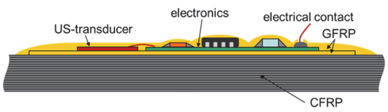
Motivation

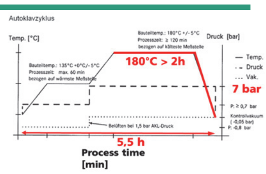
Current development targets:

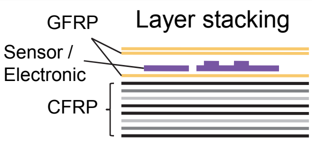
- To increase the TRL of SHM systems by improved integration concepts
- To develop an embedded system to be used in the CFRP fuselage of the Airbus A350
- To ensure
  - a high efficiency of ultrasonic wave excitation and detection
  - an autoclave process integration
  - a long lasting field operation (improved reliability)

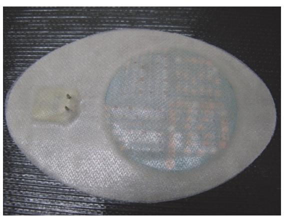


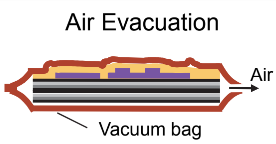
Challenge 1: Lamination process integration

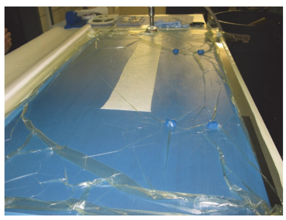


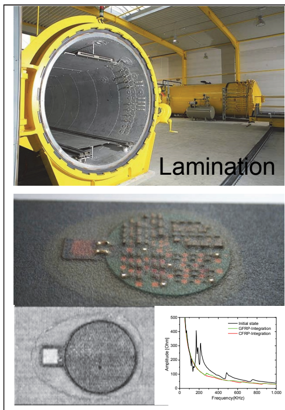






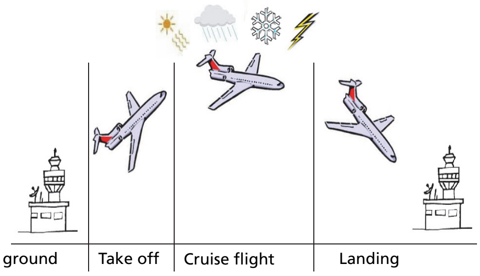






Challenge 2: Loading Conditions During Flight → Material Degradation over Time (Structure and SHM system!)

Different flight stages



Environmental loadings during flight

#	Factor	Value Range
3	Temperature cycles	-55/ +85°C
4	Max. strain (uniaxial)	0,3% 0,2% - cyclic
5	Vibration	0,2g²/Hz
6	Moisture	til 90% r.H.
7	Mechan. shock	6-10g at 90Hz

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Challenge 3: How to Develop an Appropriate POD Approach for embedded SHM Systems ?

- The reliability of conventional NDE systems with one or a few moving sensors can be adequately described by classical POD concepts (e.g. Berens, POD as a function of flaw size).
- In the case of Lamb wave based structural health monitoring (SHM) the situation is more complex.
- In SHM a larger number of permanently installed sensors arranged in a network configuration are often used. For this problem the conventional POD concept needs to be extended since POD becomes a function of position or more general, a function of the specific network configuration.
- Moreover, the long-term behavior of structure, sensors and electronics plays an important role since their degradation directly affects the POD of the SHM system over time

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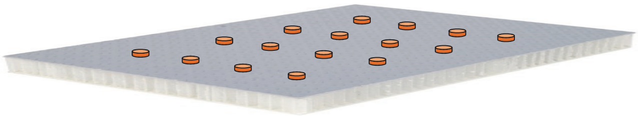
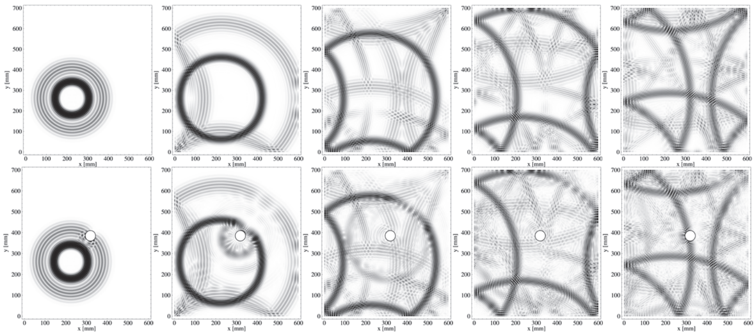
SHM-POD as a Function of Position: Total Focusing or Synthetic Aperture Concept



Reference state

Actual state



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SHM-POD as a Function of Position: Total Focusing or Synthetic Aperture Concept

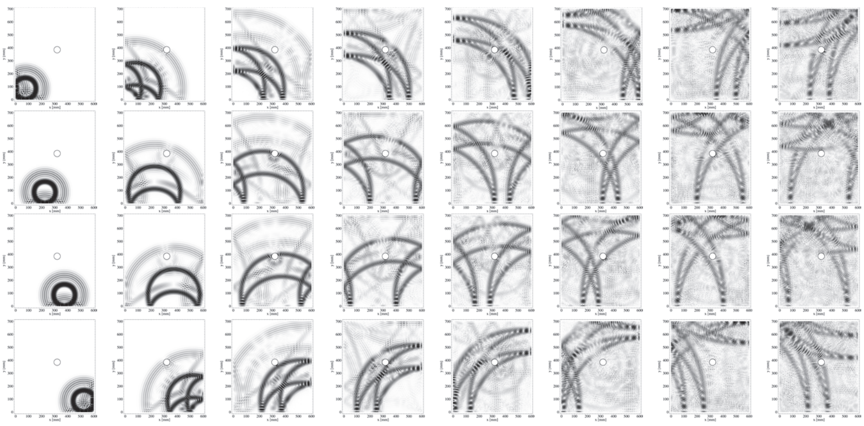
Actuator 1

Actuator 2

Actuator 3

Actuator 4

⋮



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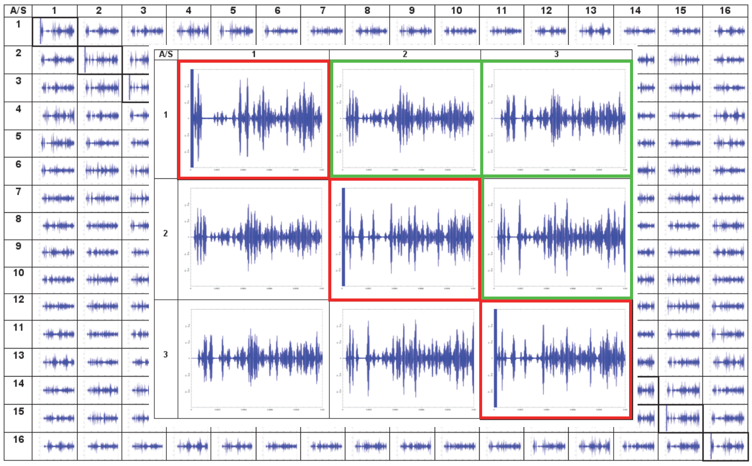
SHM-POD as a Function of Position: Total Focusing or Synthetic Aperture Concept

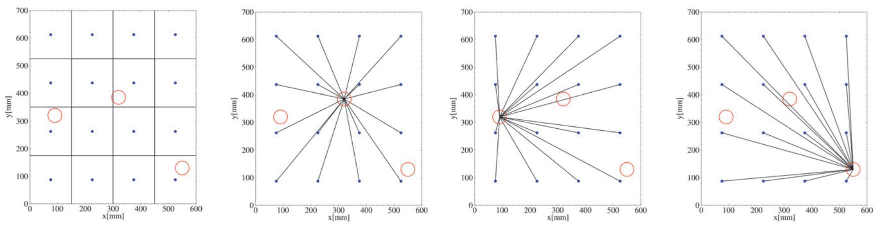


Pitch-catch data

Pulse-echo data

Symmetric in a linear system!

SHM-POD as a Function of Position: Total Focusing or Synthetic Aperture Concept



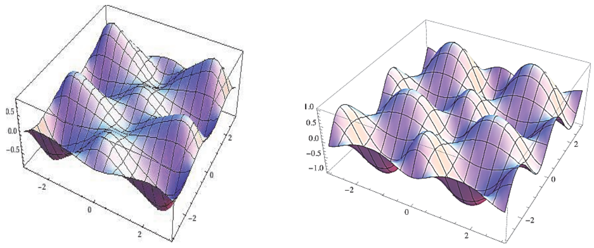
- Transducers
- Potential defects (hole, delamination, corrosion, cracks etc.)

Total focusing ray paths (beamforming)

SHM sensor network in total focusing mode can be considered as a special case of an ultrasonic scanning device!

However, the POD becomes a function of position (of the focal point relative to the sensor network)

SHM-POD as a Function of Position: Total Focusing or Synthetic Aperture Concept

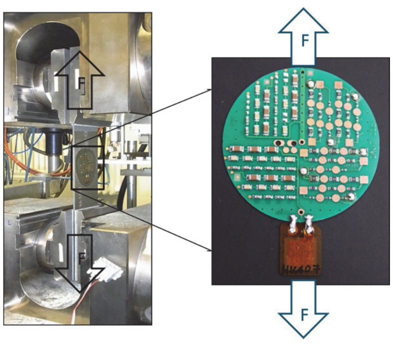


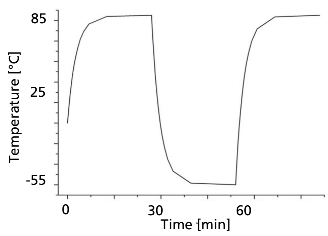
POD Landscapes: Local height represents the maximum amplitude that can be obtained by the total focusing method.

(Needs to be corrected by the flaw orientation for non-axisymmetric defects).

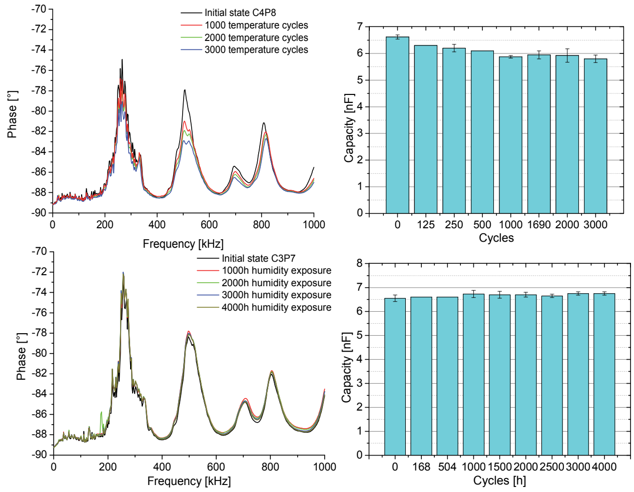
SHM-POD as a Function of Life Time: Quantification by Fatigue & Environmental Tests

- **Mechanical Tests**
- **Temperature Cycle Tests**
- **Humidity Exposure Tests**





SHM-POD as a Function of Life Time: Quantification by Fatigue & Environmental Tests



Temperature cycle test of piezo sensor (-55°C to 85°C)

Damp/Heat test of piezo sensor (85°C at 85% rel. H.)

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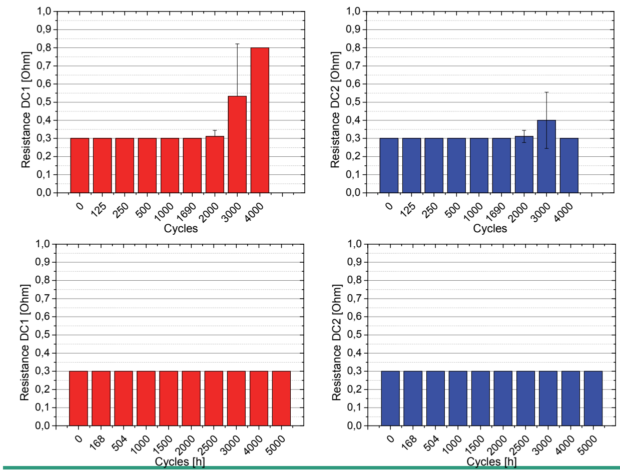
SHM-POD as a Function of Life Time: Quantification by Fatigue & Environmental Tests



Temperature cycle test of electronics (DC1 & 2) (-55°C to 85°C)

Damp/Heat test of electronics (DC1 & 2) (85°C at 85% rel. H.)

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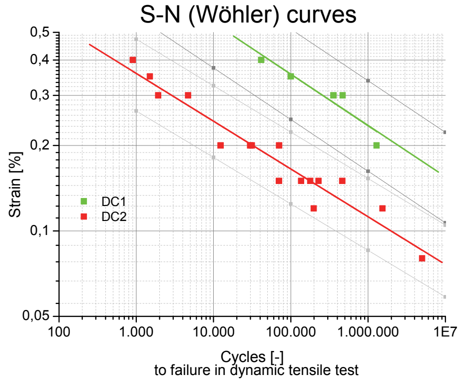
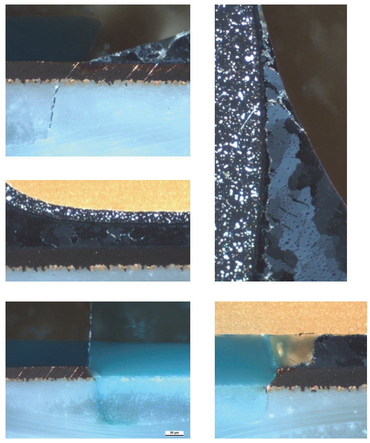
SHM-POD as a Function of Life Time: Quantification by Fatigue & Environmental Tests

Fatigue Life Evaluation by S-N (Wöhler) curves





Microscopic failure analysis

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SHM-POD as a Function of Life Time: Quantification by Fatigue & Environmental Tests

Test	Requirement RTCA DO-160F	Test conditions	Load in hours successfully compl.
High-temp.test Low-temp.test Damp/Heat TCT	110°C,24h / 180°C,3,5h -55°C, 24h 55°C,95%r.H., approx. 120h -55 - 85°C 10K/min. 2Cyc	180 ± 5°C -70 ± 1°C 85°C / 85%r.H. -55/85°C (1Cyc.=1h)	24 24 4000 3000
			Cycles successfully compl.
stat. Pulltest dyn. Pulltest	Ɛ=0,15-0,3% *	Ɛ=1% Ɛ=0,08% Ɛ=0,12% Ɛ=0,15% Ɛ=0,2% Ɛ=0,3%	Ok 5.000.000 198.000 212.000 44.000 2.000

Equip SHM system with additional temperature, humidity & strain sensors → Determine fatigue life and loss of performance of SHM system → Correct POD from initial state value

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Summary

- The initial POD of an embedded SHM system can be determined after the lamination process
- A Lamb wave sensor network in TFM mode can be considered as a special case of a mechanical ultrasound scanner. Thus, the conventional Berens approach is applicable in general.
- Since POD becomes a function of position the Berens approach needs to be corrected by the concept of POD landscapes
- Since POD also becomes a function of time the results of fatigue, environmental and functionality tests together with online sensor data of temperature, humidity and strain can be used to determine the current POD of the SHM system (< initial POD)

→ Break-Out-Session on Reliability of SHM