Comparison of NDT Techniques to Evaluate CFRP - Results Obtained in a MAIzfp Round Robin Test

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Abstract. Fiber reinforced polymeric materials are used for lightweight constructions and are an integral part of cars, airplanes or rotor blades of wind turbines. Non-destructive testing (NDT) methods play an increasing role concerning the manufacturing process and the inspection during lifetime. The selection of the best NDT technique for a certain application depends – of course – on many factors including the type, position and size of the defect to be detected but also on secondary issues like accessibility, automation, testing costs, reliability and resolution to mention only some.

For the more technical-scientific part of these issues, the determination of the probability of detection (PoD) plays a significant role. Early in the design process questions should be raised concerning the probability with which certain attribute of interest (a defect that has an effect on the structural behavior) can be detected (and localized) in a certain construction. Several defect types have been identified to be critical like impact damages, undulations and porosity. Test samples out of differently processed Carbon Fiber-Reinforced Polymers (CFRP) as used in the automotive or aeronautical industry have been produced including defects of different type and size. In order to determine the PoD and to check whether a technique is applicable the different partners applied a broad variety of selected NDT techniques including Micro CT, Ultrasound (including phased-array and air-coupled UT), Active Thermography, Eddy Current, Vibration and Visual Analysis and Local Acoustic Resonance Spectroscopy (LARS).

The presentation will summarize some of the results of the experiments and ongoing data analysis.

Introduction

The cluster project *MAI Carbon* is one of the Leading-Edge Clusters sponsored partly by the German Federal Ministry of Education and Research to support the metropole region of the cities Munich, Augsburg and Ingolstadt in Bavaria fostering the further development and application of lightweight constructions out of carbon fiber-reinforced polymers (CFRP). As part of this Leading-Edge Cluster the subproject, MAIzfp is dealing with "Combined NDT methods for quality assurance of fiber-composites". The overall goals and some of the findings of this subproject are described in another proceedings paper of this conference [Sause et al. 2016].

This paper refers the used methods and some of the results that were obtained in non-destructive testing and round robin experiments conducted by some of the partners of the MAIzfp project, namely Airbus Group Innovations, Airbus Helicopters Deutschland GmbH, BMW AG, Siemens AG, TU Munich and University of Augsburg. Due to ongoing data analysis and existing confidential agreements, only some results can be presented in the following.

1. **Concept for the development and application of NDT and SHM techniques**

The characterization of fiber-reinforced composites in the frame of quality control is a complex task. The efficient integration of non-destructive inspection and structural health monitoring techniques into the production process and the maintenance procedures requires an adequate holistic concept that is composed out of several modules (Fig. 1). If the selection of the most suitable NDT or SHM technique (or their combination) is considered (Fig. 1, center), this has to be based on a clear definition of the requirements (Fig. 1, upper left). It is certainly helpful to determine the defect type, size and location under consideration as well as the required Probability of Detection (PoD). Only defects that have an effect on the structural integrity or that lead to a loss of required properties (Effect of Defect EoD) are desired for detection [Oster 2012].

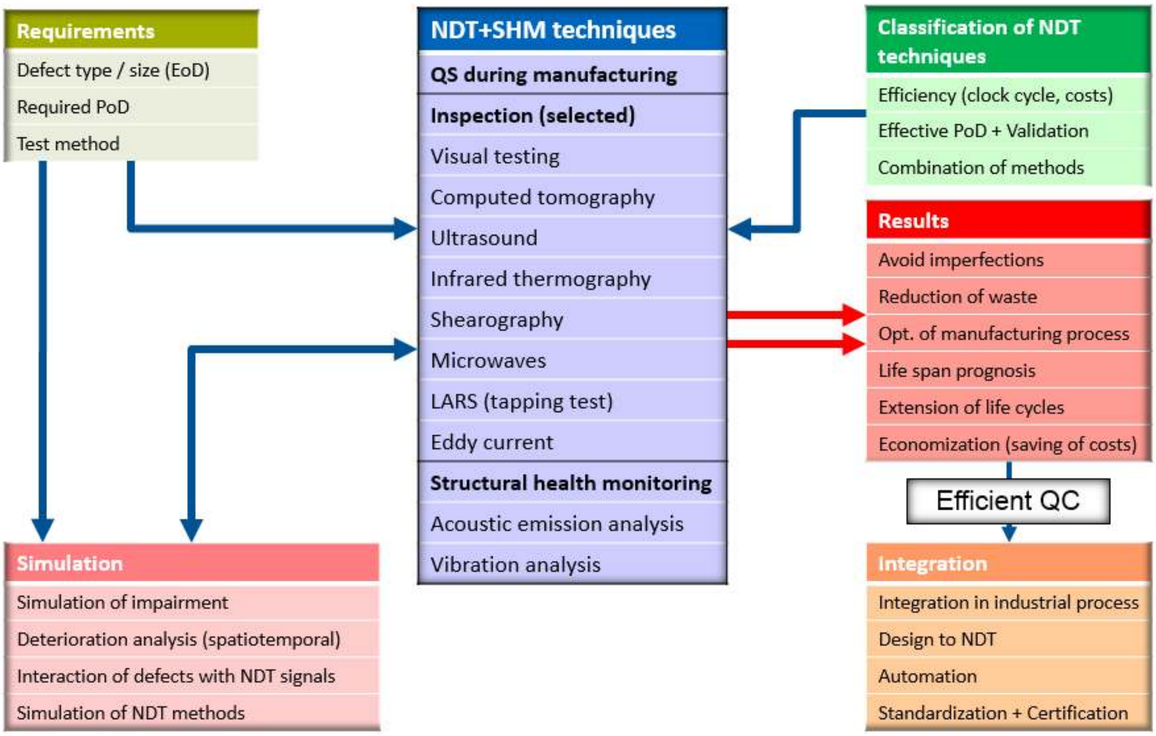

Fig. 1. Holistic concept for an efficient selection of NDT and SHM techniques in the context of quality control [Grosse 2014]

The combination of testing techniques with simulations (Fig. 1, bottom left) is another way to increase the efficiency. Finite element techniques are often applied to simulate the reaction of a component to a static or dynamic load. However, numerical models need the input from measurements to define the boundary conditions for the simulation and to validate the approach taken. NDT can give valuable input and – on the other side – needs simulations as well to reduce the complexity of measurements at heterogeneous structures such as CFRP. Simulations are not restricted to study the effect of loads but can be applied also to the non-destructive testing process itself. However, this is a matter of another paper in these proceedings [Zelenyak et al. 2016] describing the application of numerical simulations for NDT techniques.

However, there are other factors as well (Fig. 1, upper right). The efficiency of non-destructive inspections is based on the clock cycle as well as on the required investment for equipment and personal (training, qualification). The required PoD needs to be crosschecked with the effective PoD in regard to the chosen techniques and the defect types. This can lead to a classification of NDT techniques for a certain application. A combination of techniques (NDT and simulation) can further optimize the procedure.

2. Materials and defect types

As a first step, the MAIzfp partners from the industry indicated imperfections that are most crucial for the components and materials under consideration. Multilayered CFRP laminates from the automotive and the aeronautical industry have been tested. Samples without imperfections (control group) were tested against samples with different types of defects including impact damages, undulations and porosity.

As for the impact damage detection, four different sets of laminates were used, two from automotive with impact energies between 3.5 J and 15 J. The impact energies used for the two sets from aeronautic ranged between 5 J and 12.5 J. The dimension was always 150 mm x 100 mm with a thickness of 2.1 mm (automotive) and 3.75 mm ± 0.25 mm (aeronautic), respectively. Fig. 2 displays the backside of two specimens impacted with 3.5 J (left) and 15 J (right). Three more blind samples were included in the test series that had dimensions similar to the automotive samples with impact damages. It was the task of the individual groups to determine the type and size of possible defects in these samples.

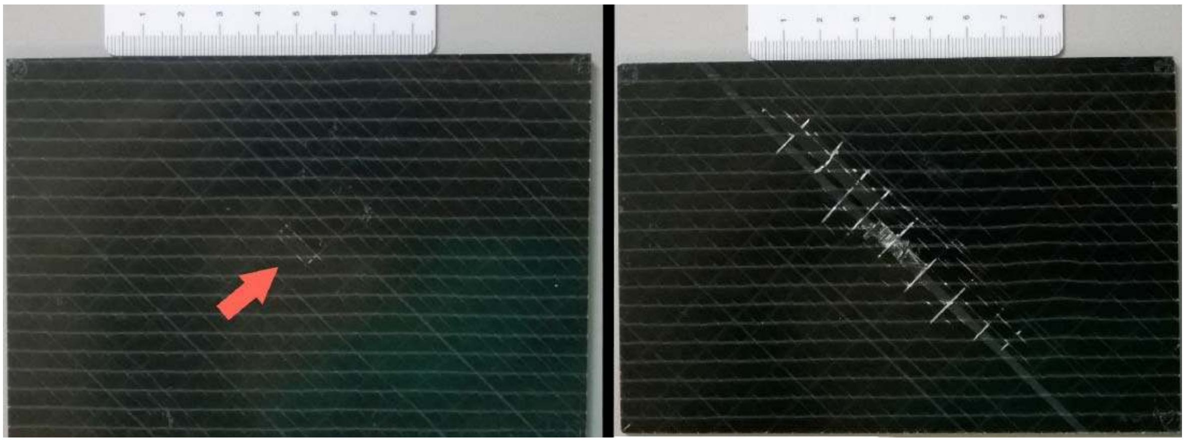

Fig. 2. Example of CFRP samples with impacts of 3.5 (left) and 15 J (right)

The samples with porosity artifacts consisted of two series with six plates. The porosity samples from automotive (Fig. 3) had a dimension of about 420 mm x 200 mm with a thickness of 1.8 mm, 1.9 mm and 2.5 mm and zones with different porosity content. The aeronautic samples had a dimension of 420 mm x 200 mm with a non-uniform thickness and nine different porosity zones.

Since undulations are identified as being critical as well, two different sets of such probes were also investigated. One set with three samples from automotive had dimensions of 360 mm x 200 mm and a thickness of 2 mm. Another set from aeronautic with six specimen of dimensions 185 mm x 33 mm and a thickness of 5.5 mm (a sample is depicted in Fig. 4) were tested as well. Some of the undulations were out-of-plane and others in-plane.

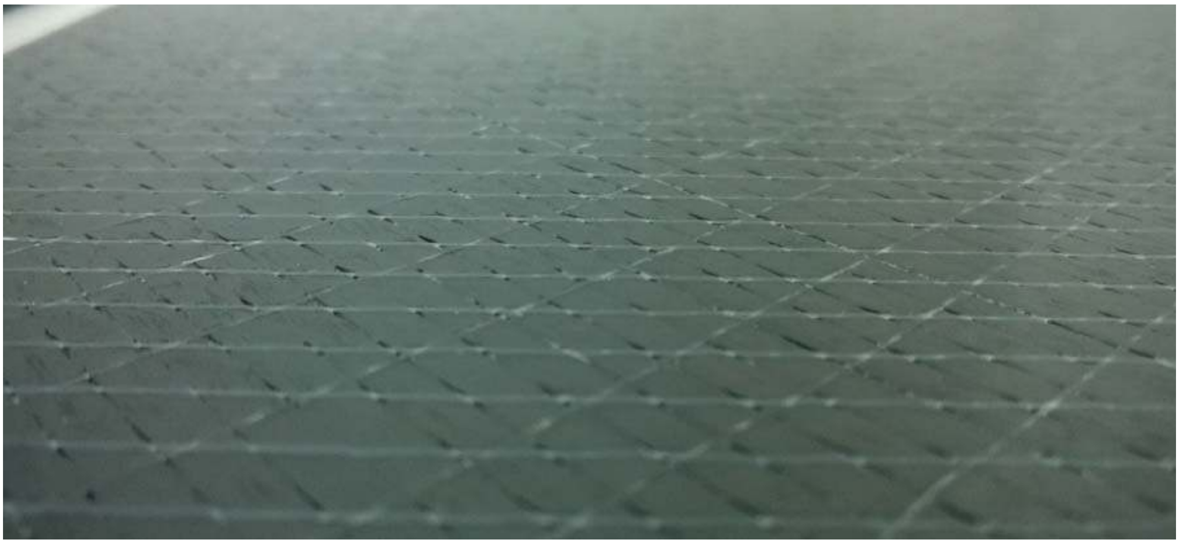

Fig. 3. Example of a CFRP specimen with porosity

Moreover, several test specimens with a collection of artificial defects like blind holes and delaminations, as the one described by Perterer [2012], have been examined as well.

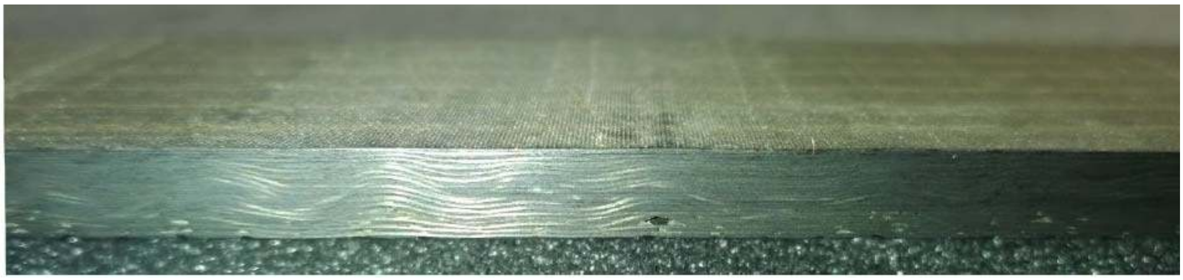

Fig. 4. CFRP sample with visible out-of-plane undulations

3. NDT techniques

There is a wide variety of NDT methods being applied in the frame of the project. Acoustic methods like ultrasound in through-transmission and reflection using different setups, sensors and coupling techniques were used but also electromagnetic and other testing techniques. A none-comprehensive list is included in Table 1. Several of these techniques have been included in the round robin experiments, in particular RT, UT and Optical Lockin Thermography (OLT) since these are the most widely used techniques to detect the defect types by the partners. Some of the results of the OLT experiments along with the evaluation of PoD values are discussed in section 5. However, all other techniques mentioned in Tab. 1 (and some more) have been applied and some of them are depicted in Fig. 5.

Table 1. Some of the NDT techniques used in MAIzfp

acoustic	**electromagnetic**	**other**
Ultrasound (UT) – Immersion – coupled single transducer – phased-array – full-matrix capture – air-coupled (ACU) Acoustic emission analysis Bond testing – Local acoustic resonance spectroscopy (LARS) – Tapping test Vibration and modal analysis	Radiographic testing (RT) – CT scanning – Laminography Infrared Thermography – Active Lockin Eddy current testing	Optical testing – Laser triangulation – Shearography – Digital image correlation

Results of the measurements are not only summarized in the following but also in other papers of these proceedings as it is the case for ultrasound full matrix capture [Grager et al. 2016] and resonance techniques [Mueller et al. 2016]. Another paper is dealing with a combination of thermography and acoustic emission techniques [Goldammer et al. 2016].

Fig. 5. Some of the NDT techniques applied (from left to right): ultrasound phased array, optical lockin thermography, bond testing and vibration testing using a microphone

3.1. Development of new NDT techniques

The group took the opportunity to test during the project even a new ultrasonic sensing technique, which uses a Fabry-Pérot-Etalon instead of piezoceramic materials or membranes [Guruschkin 2015]. Guruschkin showed in a close collaboration between the *Chair of Non-Destructive Testing (TUM)*, *Siemens*, *Xarion Laser Acoustics* and *Airbus Group Innovations*, that an optical microphone [Fischer et al. 2015] can successfully replace the receiver probe and its required preamplifier [Hillger et al. 2012] in a commercial ACU system (Fig. 6). This novel acoustic sensor without any moving parts uses the resonance of a compact and rigid Fabry-Pérot-Etalon, which is open to air. The transmitted wavelengths of the laser are altered by the refractive index of air and hence by the sound pressure in the cavity at the tip of the microphone. This optical sensor provides a high dynamic and frequency range and has the major advantage for ACU systems, that one ultrasonic air-solid transition is eliminated.

Fig. 6. Optical microphone (left) and novel configuration for ACU measurements (right) [Guruschkin 2015]

The first results with this novel ACU through-transmission configuration, showed improvements in terms of resolution, especially when the optical microphone was placed close to the surface of the CFRP test plate in Fig. 7.

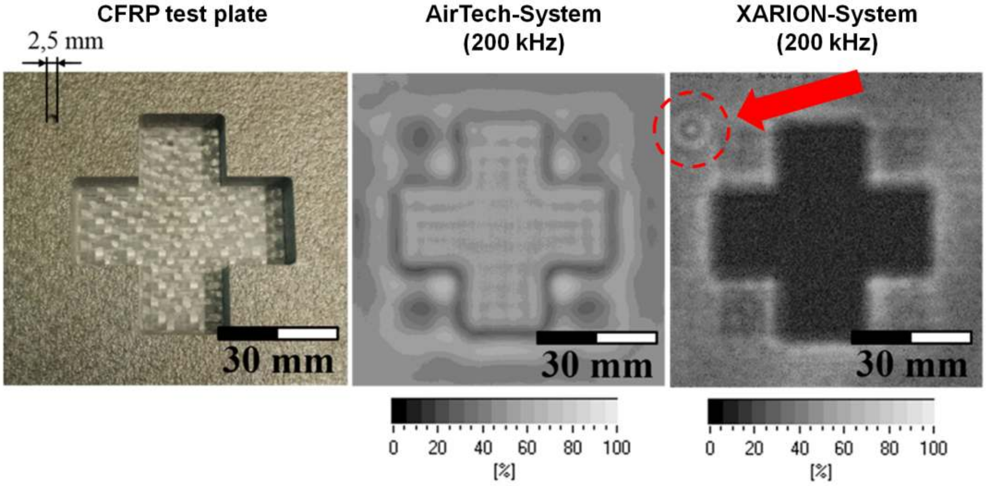

Fig. 7. Backside of a CFRP plate with a flat-bottom hole of 2.5 mm in diameter (left). The hole cannot be resolved in the C-Scan of the conventional system (middle), but is clearly visible with the novel configuration (right) [Guruschkin 2015]

New ultrasonic transmitter or evaluation concepts are necessary, to fully exploit the improved resolution by the optical microphone.

During the production of the microphone, its sensitivity can be tailored according to the expected sound pressure conditions on the receiver side of the ACU measurement configuration. Further improvements in terms of signal-to-noise ratio are expected with a new sensitivity-adapted sensor.

4. Data analysis

As described in section 2 and by Kiefel et al. [2014], several sets of CFRP samples were impacted with different impact energies. Subsequent reference measurements of the damaged areas were made with ultrasonic immersion testing by using the double through-transmission technique with a point-focused 10 MHz probe. This technique was defined to be the most accurate method to determine the size of the impact damages [Summerscales 1990]. Defect sizing was performed in the recorded C-Scans by the 6-dB-drop thresholding technique [Smith 1994]. In consideration of systematic measurement errors, which affect the accuracy of this method (see, e.g. Smith [1994] and Smith et al. [1998]), these determined defect sizes were then further used as reference values for comparison with other NDT techniques.

The large acoustic impedance mismatch between solids and air is challenging for air-coupled ultrasonic inspection. This is the main reason, why the development of ACU systems was mainly probe-driven so far [Karbhari 2013]. Although many ACU probe concepts exist (e.g. Gaal et al. [2012], Nakamura [2012], Stoessel [2004]), it is still very common to use monolithic piezoceramic transducers with a matching layer of defined acoustic impedance and thickness ($\lambda/4$ at the centre frequency), to solve the acoustic mismatch problem. However, this concept tends to produce longer pulses, because first, the matching layer acts as narrow-band filter; second, the transducer is excited by long tone-bursts; and third, is often not damped by a backing material to increase the acoustic power output [Hillger et al. 2012; Nakamura 2012; Stoessel 2004]. Thus, pulse-echo testing with a single probe of this concept is not feasible and accessibility from both sides of the test object has to be ensured to perform measurements in through-transmission. Most ACU inspections are conducted with test frequencies in the lower hundred-kilohertz range, as air strongly attenuates ultrasound, especially at higher frequencies (e.g., approximately 1,6 dB/cm at 1 MHz) [Karbhari 2013]. Nevertheless, air is a uniform coupling medium that enables contactless, fast and automated testing of large and complex composite structures, like helicopter tail booms [Hillger et al. 2012].

Air-coupled ultrasound (ACU) measurements with different systems and probes from *Ingenieurbüro Dr. Hillger* (75 kHz, 120 kHz, 200 kHz, 225 kHz and 300 kHz) were conducted in through-transmission. With increasing ACU test frequency, the edges of the impact damages could be identified much more accurately, as exemplarily shown in Fig. 8.

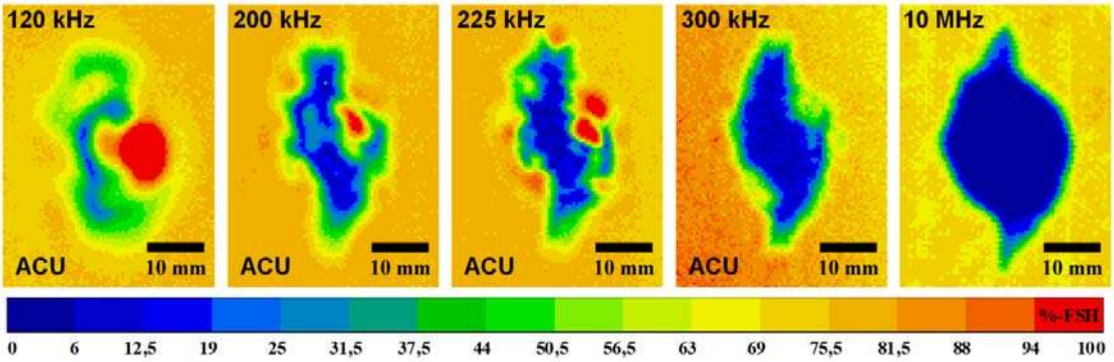

Fig. 8. ACU C-Scans of a CFRP impact damage (12.5 J) at different test frequencies. The edges of the impact damage can be identified much more accurately with increasing frequency. The C-Scan on the right was recorded with ultrasonic immersion testing by using the double through-transmission technique with a point-focused 10 MHz probe (H10MP15). Resonance effects in the impact damage are prominent at 120 kHz, 200 kHz and 225 kHz

Irrespectively of the frequency, deviations to the expected signal drop above the impact damage could be observed in almost every recorded ACU C-Scan. Note that, the inherent low-test frequencies of ACU cause wavelengths in the same order of magnitude than the laminate thickness [Karbhari 2013]. Thus, resonances in the plate transmission coefficient are often prominent in the test results, which are further enhanced by using the above-mentioned narrow-band transducers. Therefore, delaminated areas can produce higher through transmission amplitudes than non-defective areas (Fig. 6) [Hillger et al. 2004].

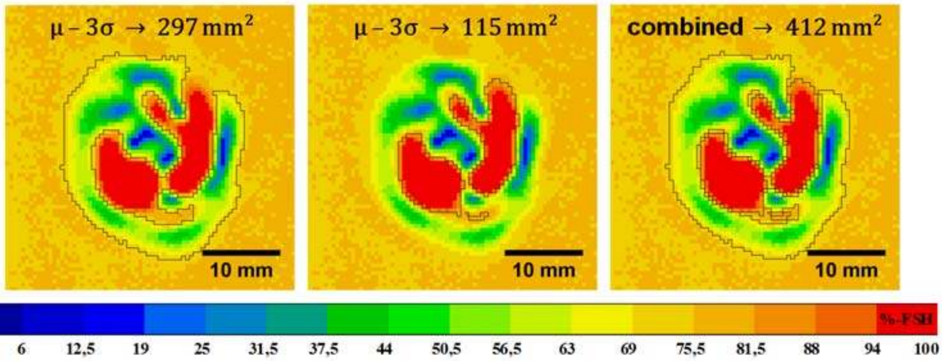

Fig. 9. Pixel segmentation in an ACU C-Scan by using a threshold for signal drop (left) and for signal rise (middle). In this case, the new thresholding technique lead to a conservative result, as the area of the impact damage was overestimated by around 12 %, compared to the reference measurements.

In fact, the 6-dB-drop technique could not be applied, as it would have significantly underestimated the damaged area. As described by Kiefel et al. [2014], a new thresholding method was developed using two thresholds for the segmentation of defective pixels in the C-Scans: One for the expected signal drop t_{low} and the other for the signal rise t_{drop}, caused by resonance effects (Fig. 9). The thresholds were calculated in non-defective areas in the C-

Scans, where the signal heights are normally distributed with mean amplitude μ and standard deviation σ: $t_{low} = \mu - 3\sigma$ and $t_{high} = \mu + 3\sigma$.

A defect indication in a phase image obtained with optical lockin thermography can have higher or lower grey values than its non-defective background, mainly depending on the excitation frequency and the depth of the defect. Thus, a method proposed by Zoecke [2009] was used for defect sizing, which offers two thresholds to choose for segmentation ($\mu \pm n \cdot \sigma$) – depending on the appearance of the defect in contrast to its background. If the phase angles in the non-defective region are assumed to be normally distributed, their mean value μ and standard deviation σ can be determined. The n value can be calculated by considering the ultrasonic 6-dB-drop thresholding technique. Here, an indication A_{sig} is only classified as being a defect, if its SNR is at least 6 dB above noise level σ:

$$SNR = 20 \cdot log_{10}\left(\frac{A_{sig}}{\sigma}\right) = 6\,dB \rightarrow A_{sig} = 10^{6/20} \cdot \sigma \;\approx 2 \cdot \sigma$$

Note that, CFRP impact damages usually consist of different sized delaminations in different depths. Thus, they can appear brighter and darker simultaneously in the phase images at a distinct excitation frequency. Prior to the segmentation process (Fig. 10), inhomogeneous background illumination effects in the phase images were corrected according to Omar et al. [2005].

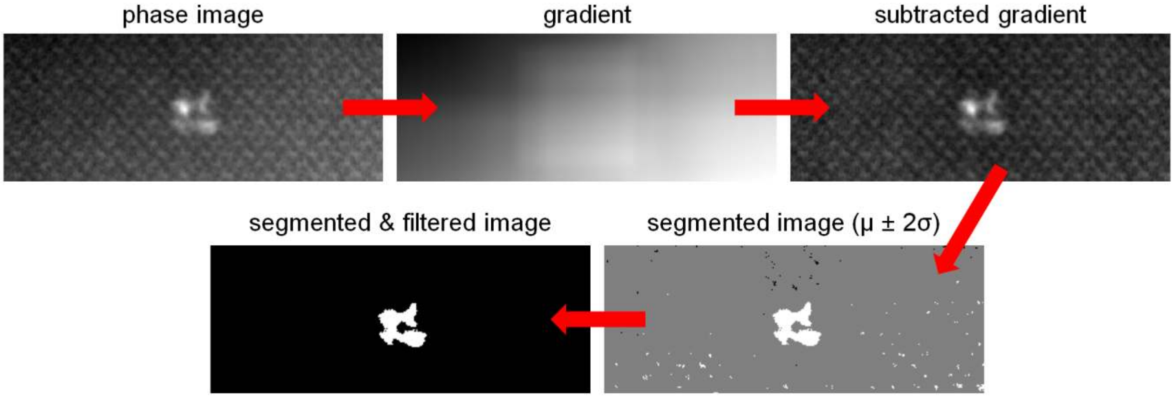

Fig. 10. Sizing of a CFRP impact damage (10.0 J) in a phase image (0.01 Hz) from optical lockin thermography. The segmentation procedure includes the subtraction of the illuminated gradient (top middle) from the original phase image (top left). After segmentation ($\boldsymbol{\mu} \pm \mathbf{2} \cdot \boldsymbol{\sigma}$), minor false indications from the fabric structure are filtered via a minimum defect size [Setz 2015].

5. Probability of Detection

In the field of non-destructive testing, the calculation of detection probabilities is a method for validating the applicability of testing methods for defined defects in components. Several different probability of detection methods can be found in literature, whereas most of the applied PoD methods come from aeronautic and aerospace industries. Schnars & Kück [2009] summarized three well-known approaches: the *29/29-*, *Hit/Miss-*, and *Signal-Response* analysis. The following study on PoD is based on the evaluation of signal responses by using the analysis technique described in Berens [1989]. As mentioned in section 3 several NDT techniques and defect types have been evaluated in a Round Robin Test and only one example will be presented here selecting impact damages and OLT. The signal response $\hat{a}$ is the evaluated defect area of measurements on impact damages, using optical lockin thermography from rear-side of the samples. Depending on the measurement setup of the partners, the OLT measurements were carried out with lockin frequencies between 0.01 Hz and 0.8 Hz in reflection and transmission setup. The actual defect area *a* was determined by evaluating the reflector-plate echo of immersion based ultrasonic testing. Due to a full penetration of ultrasonic waves through sample thickness, it is possible to take rear-sided delaminations of laminate layers into account, which is often not possible by evaluating the back-wall echo. The signal response analysis according to Berens [1989] is a well proved PoD analysis technique at the Airbus Group and thus was used for comparative OLT validation against ultrasonic testing. The detection probability

$$PoD(a) = \Phi(Z)$$

was calculated by using algorithms which were coded in Matlab®. Therefore, the parameter determination of β_0, β_1, and σ_δ needed for

$$Z = \frac{Y - (\beta_0 + \beta_1 X)}{\sigma_\delta}$$

was done by maximum likelihood estimation (MLE), whereas instead of logarithmic signal response $\hat{a}$ and actual size a, the parameters $Y=\hat{a}$ and $X=a$ were chosen linear due to assumed linear coherence between $\hat{a}$ and a (Fig.11).

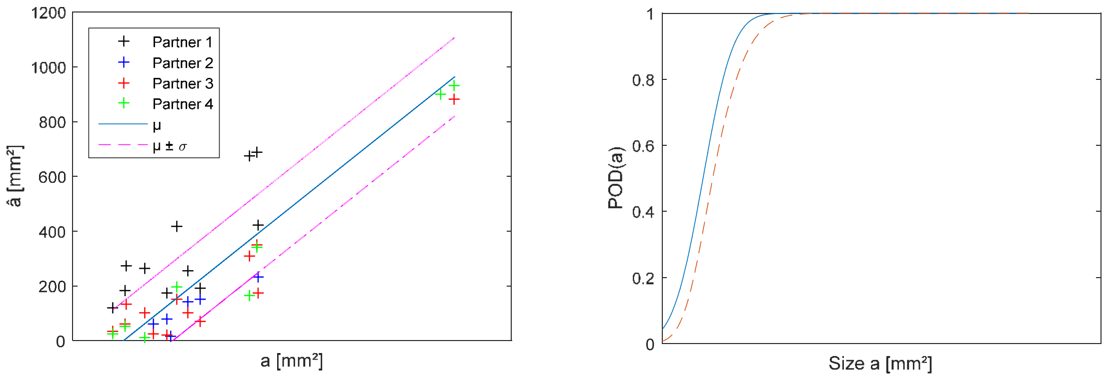

Fig. 11. Comparative OLT validation with regard to immersion ultrasonic testing of impact samples using signal response PoD analysis according to Berens [1989]. The $\hat{a}$ vs. a diagram (left) visualizes the measurement results of the individual project partners with MLE of μ and σ and is the basis for the corresponding PoD curve (right).

The PoD calculation was carried out with $\hat{a}_{dec}$=100 mm², $\hat{a}_{th}$=0 mm², and $\hat{a}_{sat}$=1200 mm². Thus, no exclusion of measurement results were done by lower thresholding or saturation, which moreover is not applicable for $\hat{a}$ data of this type. By using $\hat{a}_{dec}$=100 mm², it is conservatively assumed to indicate 10 mm x 10 mm defect damages as smallest defect size which has to be detected. As an outcome of the comparative PoD validation, it can be summarized that the $a_{90/95}$ value results in good correlation with expected values from immersion ultrasonic testing, even for combining OLT reflection and transmission techniques in $\hat{a}$ input data.

6. Conclusion and Outlook

During the MAIzfp project, a very constructive collaboration was established to share information about NDT methods to detect imperfections and defects in CFRP components of the aeronautical and automotive industry but also for other applications as well. One of the key parts of the project was the advancement of NDT and data processing techniques and the comparison of measurement setups and results. Round robin tests have been carried out to foster the results of the collaboration and to establish validation techniques as the probability of detection method. Along with destructive tests, numerical simulations [Zelenyak et al. 2016] and evaluations concerning applicability and cost-efficiency the findings of the project are an excellent basis to establish efficient NDT techniques for CFRP components.

More than 23 Bachelor's and Master's theses and more than 7 Ph.D. theses related to MAIzfp are or will be accomplished at the Chair of Non-destructive Testing of the Technical University of Munich alone. This provides for further outcomes of this collaboration that is described briefly in this paper only. A comprehensive list of all publications is available on request.

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