In-line Quality Assurance for the Manufacturing of Carbon Fiber Reinforced Aircraft Structures

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Abstract. Carbon fiber reinforced polymers are playing a key role for future aircraft structure design concepts as the newest technical developments for aircraft models B787 and A350 are showing. Due to the specific mechanical properties of this composite material and the novel manufacturing and machining techniques for large-scale CFRP made aircraft structures, it is necessary to establish an adequate process integrated quality assurance system that enables a cost-effective automated manufacturing route. Beside upcoming releases of numerous new reference guidelines based on well defined technical tolerances, it is necessary to look for non-destructive test techniques that are capable to monitor the different manufacturing steps and to detect defects and tolerance deviations within the processing route. For choosing reliable NDE techniques some key criteria as for example non-contact measurement, imaging options, penetration depth, scanning speed, the maximum possible coverage area and others have to be considered. The decisive step for applying new NDE methods is the scale up from laboratory conditions to large component testing in an automated manufacturing environment. Beside the ability to find and evaluate small microstructural features within a large CFRP structure component, it is also necessary to establish an intelligent software infrastructure which allows to exchange, compare and merge data sets of different non-destructive scanning techniques in terms of a reliable signal interpretation and evaluation.

Introduction

Recent market studies by Boeing and Airbus assume that for the next 20 years the worldwide demand on new airliners will range between 25,000 and almost 31,000 [1, 2]. The twin-aisle market, which includes efficient long-range airplanes such as the Airbus 350 and the Boeing 787 is the fastest growing segment of the market, accounting for 23 % of the delivery units, valued at approximately $ 1.6 trillion. High fuel costs and upcoming requirements of reducing pollutant emissions are compelling airlines to accelerate replacement of older airplanes. These are the main driving factors for using new composite materials on load carrying fuselage and wing structures in order to save weight and to reduce fuel consumption significantly. With the so called black airframes, the big manufacturers Airbus and Boeing are currently developing a new generation of aircrafts with a structure that contains more than 50 % composite material. However, the use of a new material class does not only mean to exchange structural parts but to revise the whole structure design, component manufacturing and joining techniques as well as the material's machining procedures and quality assurance concept. So far non-destructive inspection was usually performed with finished parts at the end of a manufacturing process. But now, focusing the primary objective of significant manufacturing cost reduction and at the same time ensure high quality standards, it is inevitable to establish an automated monitoring system which is firmly integrated in the production process chain. For example a CFRP pre-form structure which shows anomalies in the fiber layup after draping, will be removed from the process chain immediately in order to avoid the following expensive process steps. For the separated part it then has to be decided whether it will be finally rejected or undergoes more detailed non-destructive inspection procedures with higher resolution.

1. CFRP Component Design

Fiber reinforced composites are layered materials with strongly anisotropic properties. The thermal expansion rigidity and strength of these materials diverge greatly depending on the orientation of the fibers. When CFRP components are manufactured and assembled to large structures, fiber orientation always plays a decisive role. An aircraft fuselage shell can be assembled from complete core-wound CFRP tubes (Boeing design), or from several large CFRP shell segments (Airbus design). In each case, the carbon fibers run along the surface of the fuselage body in order to make optimal use of their exceptional strength. The number of seams and joints has to be kept to a minimum, as these – in the same way as openings for windows, maintenance ports and cargo hold hatches – represent weaknesses in the structure. Unlike light metal fabrications, the direction-dependent material properties of the CFRP composite determine the geometry of the components and the structural design. Furthermore, regarding handling and non-destructive inspection of CFRP components, it is a big difference to deal with a demonstrator scale (Fig. 1) or a very large sized structure of an industrial production line (Fig. 2).

Fig 1. Experimental CFRP wing structure – demonstrator scale

Fig. 2. CFRP wing structure of Boeing's Dreamliner – production line scale (Boeing)

The joining together of two large segments presents a particular challenge, as the high dimensional stability of CFRP structure components allows a tolerance of only a few microns. Fuselage shells and wing segments, which are manufactured by different supplier plants that are located several hundreds or even thousands of kilometers from each other, have to be joined together with an extremely high fit-accuracy during the final assembly process. As CFRP components cannot be welded together like light metal structures, the only possible joining techniques are gluing or riveting. However, the adhesive bonding technique is a very demanding process, and has far only been mastered to a limited extent. The developing of an appropriate verification technique, which can be used to check the characteristics of the bond, such as the surface coverage, the degree of hardening of the adhesive and its adherence to the surface of the components, is exceptionally difficult.

2. Process Integrated Quality Assurance

At the DLR Center for Lightweight Production Technology (ZLP) in Stade and Augsburg, the expertise required for cost-efficient, automated manufacturing and processing of large series of CFRP components is being acquired. In addition, a strategy for in-line quality assurance is being developed. This enables the monitoring and evaluation of individual manufacturing processes during and between the different production stages. It also means that a non-destructive testing method can be used to fully automatically monitor compliance with previously defined manufacturing tolerances based on particular properties, and that any deviations can be recognized and assessed by the analytical software system. For semi-finished products and components with properties that indicate defective structures, this can mean that they are immediately removed from the production line in order to prevent any further expensive and unnecessary manufacturing procedures. The direct benefits of a quality assurance system that is integrated into the production process can only be fully assessed when considering the costs of performing the additional testing alongside the enormous savings as a result of the removal of defective parts from the production line in an early stage. Figure 3 shows the principle of an in-line quality assurance system that is based on non-destructive evaluation (NDE) methods.

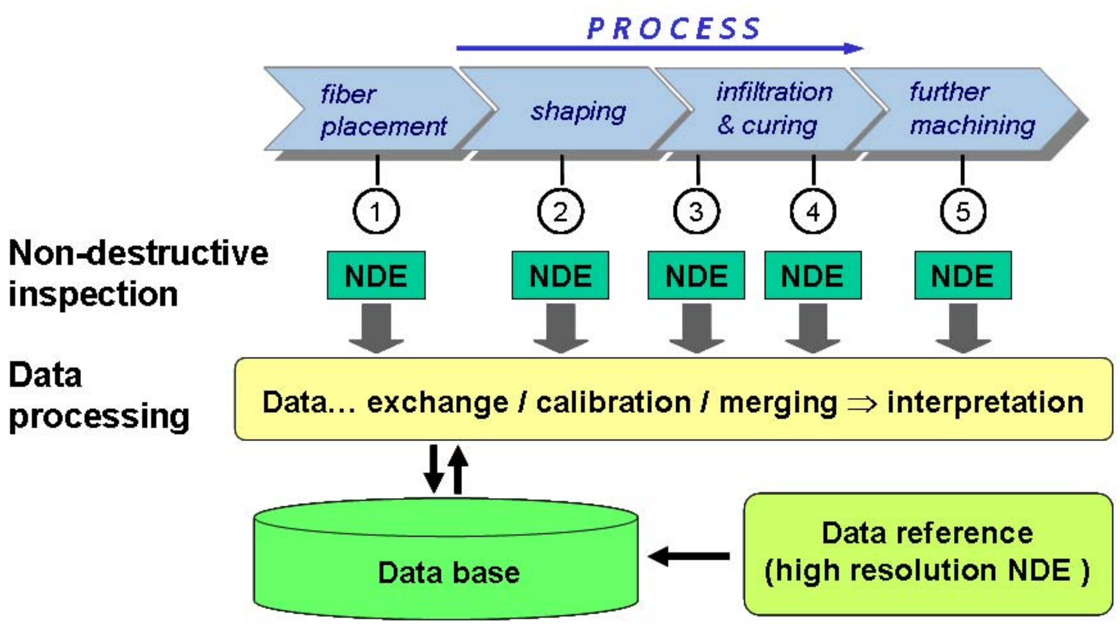

Fig. 3. Principle of an in-line quality assurance system based on NDE methods

The cost effective and efficient implementation of the non-destructive testing method in the individual processing stages requires fully automated and synchronized data acquisition and assessment that do not have substantial impact on the manufacturing process or even cause the interruption of the production line for a longer period [3, 4]. In addition an integrated data management system is collecting, exchanging and comparing NDT data from each measurement stage. Anomalies that are questionable or even minor flaws that have been detected at an earlier stage will be used as a reference for evaluation on NDT results later on in order to decide whether the component's critical area exceeds the tolerances or not. Reference data of typical failure modes based on high resolution NDT methods (e.g. computed tomography) will help to interpret the analysis data in the right way.

Figure 4 shows a concept of a multi-functional facility for CFRP component manufacturing that will be built up at the DLR Center for Lightweight Production Technology in Augsburg. Some of the robotic arms are supposed to carry the large CFRP components and bring them in the right position for further processing. The smaller robots are carrying machining tools and measurement heads, so called "end-effectors", for the following machining steps and purposes of non-destructive measurements. This facility will be capable to process large components of several meters in length.

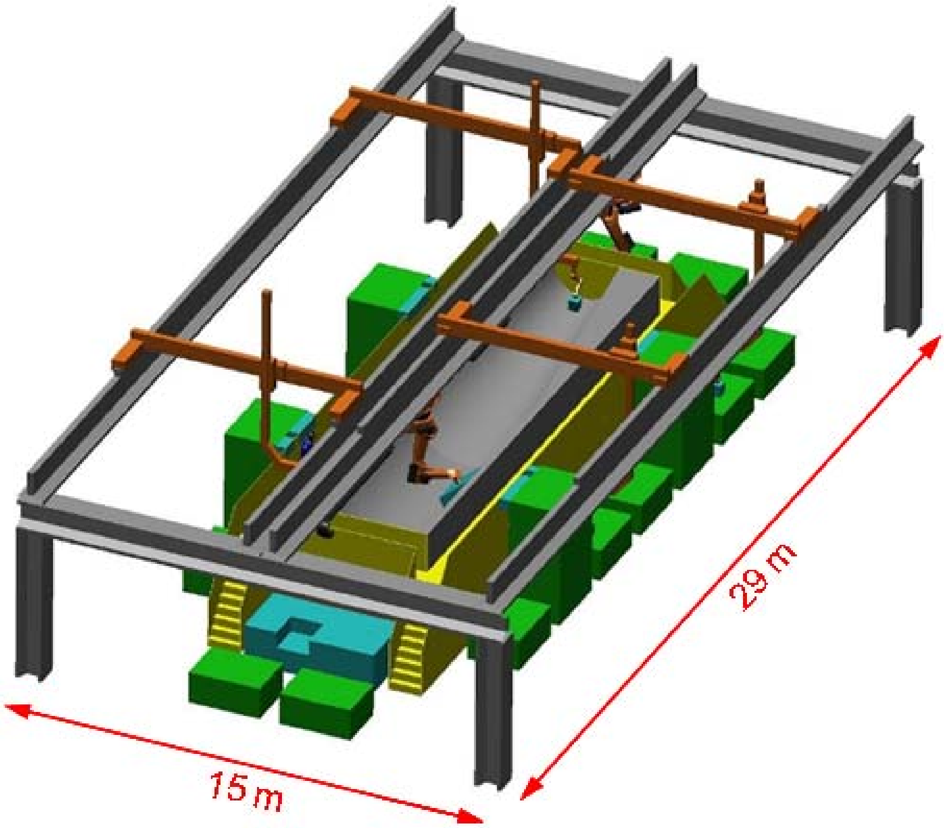

Fig. 4. Multi-functional manufacturing cell for CFRP structures (KUKA Systems)

3. Non-Destructive Testing and Evaluation

3.1 Selection of Non-Destructive Inspection Methods

Beside the well known key criteria like non-contact measurement and imaging options as well as the maximum failure detection resolution and defect selectivity even more aspects have to be considered: the penetration depth into the component's material, the scanning and measurement speed, the coverage area as well as the accessibility of the structure which means that the component's body might be accessible only from one side (reflection measurement) or from both sides (transmission measurement). However, the probably most significant requirement for process integrated non-destructive inspection is the time that is needed for measurement and data evaluation. Therefore the measurement speed and the coverage area are quite important issues. For example with commonly used ultrasound inspection techniques the transducers are moved over the component's surface line by line until the whole area is scanned. This requires a lot of time and as soon as the component's shape includes curved or ribbed areas, it may become difficult to receive proper signals of the material's interior structure. In contrast, the main benefit of optical inspection methods is the coverage of large areas within one relatively short exposure time period but on the other hand only features which are located near the component's surface can be detected at all. Literature is giving a good overview about the pros and cons of several non-destructive test methods (e.g. optical, acoustic and radiation methods) and the technical limitations in general for inspecting polymer matrix composites [5 - 7].

However, after a first review by the authors, it seems that lock-in thermography and air-coupled ultrasound are two promising options for non-destructive test methods that make a good compromise of all these boundary conditions. Both techniques are described more in detail in the following two chapters.

3.2 Lock-in Thermography

Lock-in Thermography is based on the idea that temperature modulation induced from outside the surface of the component propagates as a "thermal wave" inside the material. As this wave undergoes reflections at boundaries and surfaces like all other waves, there will be numerous reflecting waves coming back from the component's rear side and all internal interfaces. As a consequence, the temperature modulation at the component's exposed surface is modified by thermal waves coming out from the inside of the structure. A sensitive indicator of the responding thermal wave is the phase angle between energy deposition and local thermal response. The resulting surface temperature field is monitored during the modulated illumination with a thermography camera that takes a sequence of infrared images. A Fourier analysis performed at each pixel of the sequence of infrared images provides information of the magnitude and phase of the local response wave. These two parameters may be used to illustrate the relevant information in a different kind of imaging. The magnitude image is affected by inhomogeneities of optical surface absorption, infrared emission and distribution of optical illumination. Nevertheless, when the evaluation is performed for each pixel of the image sequence, all these physical effects will be eliminated. Hence, the so called phase image does not show any of these disturbing effects at all. Figure 5 shows a typical test assembly as used at the NDE labs at DLR. The thermographic camera that is used here is a JADE III long wave infrared camera from CEDIP (spectral sensitivity: 7.7 - 9.3 µm; thermal sensitivity: 35 mK). The thermal energy is applied by 4 halogen spotlights with a power of 1200 W each [9]. With the test assembly that was used for inspecting the aircraft rudder flap, as depicted in Figure 5, the resulting phase image at 0.01 Hz is shown right beside in Figure 6. As indicated by the scale, the colours represent the time displacement (phase shift) of the responding thermal waves reflected by the internal material and structural features of the CFRP component. The corresponding phase images obtained by some other excitation frequencies are shown in the gray-scale image sequence in Figure 7 below. Beside some of the rivets near the edge, there are a number of internal reinforcement elements that are clearly visible at lower excitation frequencies. The so called phase image is a result of locally different thermal diffusivity in the rudder flap's structure.

According to the thermal diffusion length μ it is possible to obtain information about the geometry and location in depth of any defect of the surface region which lies in the range of the obtainable resolution of the infrared camera. The thermal diffusion length is given by:

$$\mu = \sqrt{\frac{2\lambda}{\omega \cdot \rho \cdot c_p}} \qquad \Rightarrow \qquad \mu = \sqrt{\frac{2\alpha}{\omega}} \qquad (1)$$

Where the angular velocity of modulation is defined as $\omega = 2\pi{\cdot}f$ [s^{-1}], the thermal conductivity is λ [$W{\cdot}m^{-1}$], material density is ρ [$kg{\cdot}m^{-3}$], the specific heat capacity is c_p [$J{\cdot}kg^{-1}{\cdot}K^{-1}$] and α denotes the thermal diffusivity. The signal magnitude is affected by boundaries in a depth that is less than μ while the signal phase still responds about twice this depth [10].

Fig 5. Lock-in thermography analysis of an aircraft rudder flap made of CFRP material

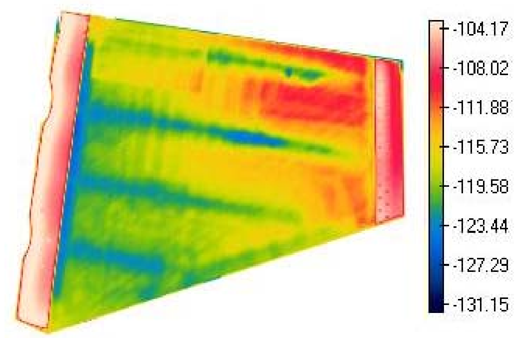

Fig. 6. CFRP aircraft rudder flap with internal reinforcement structures

Lock-in thermography is a test method which enables widespread scans on structure components. The maximum exposable surface area may be in the range of about 1 m^2 and the standard measurement time is varying in the range of a few minutes. A coupling media is not needed and single side accessibility to the structure component is absolutely sufficient as long as the wall thickness does not exceed 5 to 6 mm. The phase image shown in Figure 6 was obtained with an excitation frequency of 0.01 Hz with a total measurement time of 200 sec. As indicated by equation (1), phase images taken with lower excitation frequencies *f* show details from increasing material depth. The gray-scale phase images in Figure 7 are the results of the measurements with excitation frequencies at 0.3 Hz (left), 0.06 Hz (middle) and 0.01 Hz (right). At highest excitation frequency (left) there are mainly surface features visible such as the text on the label, the rivets and the carbon fiber orientation. With lowest excitation frequency (right), it is not so much the carbon fiber orientation but the attachment areas of the internal stringers that catches someone's eye.

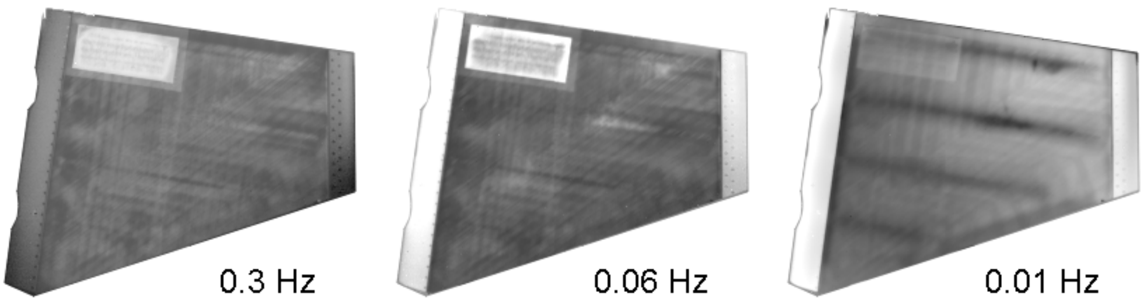

Fig. 7. Gray-scale phase images of lock-in thermography measurements at different excitation frequencies

3.3 Air-coupled Ultrasound Inspection

Ultrasound testing is the only non-destructive inspection method that is fully accepted and certified for quality assurance of component manufacturing, maintenance and repair applications in aviation industry. Most techniques are performed with water as coupling media. However, air-coupled ultrasound is still used for exceptional cases only and is not certified for industrial use in the same degree [6]. Air-coupled ultrasound techniques are contact free measurement methods that do not need a liquid media for coupling. This makes it also suitable for measuring porous materials and semi-finished pre-forms or fabric lay-ups. For limited accessibility to the component it certainly is inevitable to use a single-side measurement assembly [11]. The test facility that is used at the DLR labs is operated in a transmission measurement mode. Here the colours of the C-mode scan show the material's transmittance of ultrasound. Dark colours (dark blue or black) are indicating a maximum attenuation of the acoustic signal due to increasing porosity or occurring delaminations. Figure 8 shows a C-mode scan of a CMC load introduction. One of the two joining interfaces – outlined by the dashed rectangles – shows an area of dark blue colour which indicates increased porosity. For comparison, the CMC component was also inspected by microfocus computed tomography (Fig. 9). In the 2-dimensional µ-CT layer trough one of the component's two joining interfaces, the size and asymmetric distribution of the pores is clearly visible. With the visualization software (VG Studio Max) it is even possible to display the 3-dimensional model of the load introduction component in a semi-transparent way and to show the porosity size distribution indicated by a spectrum of colours (Fig. 9, top right). This is a good example for a better defect signal interpretation when using high resolution inspection methods for reference purposes. An interpretation of defect signals obtained by fast and large area scanning inspection methods (e.g. lock-in thermography, air-coupled ultrasound), may be much more precise and meaningful when it is compared to reference data from high resolution measurements (e.g. µ-CT) performed on comparable components with typical defect patterns.

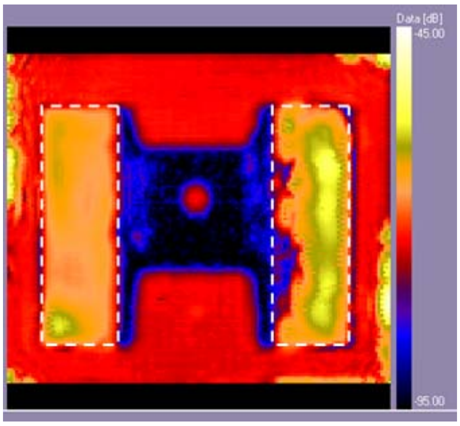

Fig 8. Air-coupled ultrasound scan of a CMC load introduction

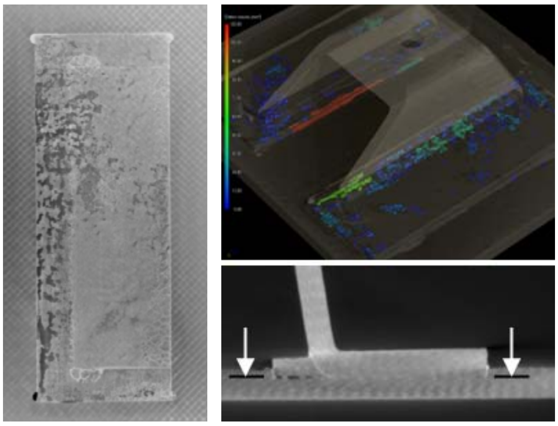

Fig. 9. 2D/3D CT-inspection results of the CMC load introduction component [12]

4. Concluding Remarks

Non-destructive test methods for process integrated inspection have to fulfill a bunch of specific requirements. One of the challenges is the task to find and evaluate all relevant microstructural details in the materials and structures that are necessary to guarantee for safety and quality of the final CFRP structure components. It will be also a challenge to scale up the measurement techniques and data evaluation of suitable test methods from laboratory conditions to large scaled CFRP structures under production line conditions. For application of non-destructive testing in the multi-functional manufacturing cell, a specific end-effector for each test method has to be developed that allows to measure at each point of the large CFRP component. The NDE measurement equipment will be mounted on a robot system to be capable to monitor every single stage in between the manufacturing procedures, performed by other robot systems. Figure 10 is a schematic illustration that shows this scenario with a conceivable measurement head for lock-in thermography inspection (OLT).

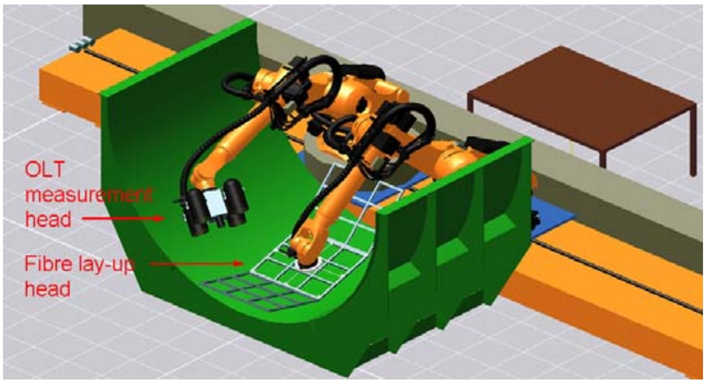

Fig. 10. Large area lock-in thermography measuring head which is mounted on a robotic system (left)

However, the main objective of an in-line quality assurance system for CFRP structure component production is not to establish new methods of non-destructive test technology and detecting defects with highest possible resolutions but to improve every single manufacturing step and to avoid the implementation of flaws. Hence, the overriding issue is the optimization of automated manufacturing procedures and the minimization of costs.

References

[1] Airbus press release, 17 September 2009. Detailed information: Global Market Forecast 2009-2028 (2009); http://www.airbus.com/en/gmf2009/data/catalogue.pdf

[2] Boeing Current Market Outlook 2010-2029 (2010). Available at: http://www.boeing.com/cmo/

[3] T. Ullmann and T. Schmidt: "*Precise down to the last detail – Quality assurance in the aircraft industry: leaving nothing to chance*", DLR Magazine 126 (2010), p. 26-29

[4] T. Ullmann and T. Schmidt: "*In-process Quality Assurance: the Key for cost-efficient Manufacturing*" (in German), Konstruktion, Springer/VDI-Verlag, 6/2010 (2010), p. 44-45 (IW6-7)

[5] C. Weimer, A. Miene, E. van Landuyt, V. Krajenski, B. Köhnke, F. Stadler, S. Preussler, M. Göttinger, T. Bischoff and F. Löhr: „*Process Attendant Failure Analysis (PROSA) – a Significant Component for Cost-Efficient Manufacturing and Analysis of CFRP Structures*" (in German), DGLR-Jahrbuch 2006, Vol. III (2007), p. 1633-1643

[6] U. Schnars and R. Henrich: "*Applications of NDT Methods on Composite Structures in Aerospace Industry*", Online-Proc. Conf. on Damage in Composite Materials – CDCM2006, Vol. 12, No. 12 (2006). Available at: http://www.ndt.net/article/cdcm2006/

[7] H.T. Yolken and G.A. Matzkanin: "*Nondestructive Evaluation of Advanced Fiber Reinforced Polymer Matrix Composites – A Technology Assessment*", NASA/CR-2009-215566 (2009)

[8] G. Busse, D. Wu and W. Karpen: "*Thermal Wave Imaging with Phase Sensitive Modulated Thermography*", J. Appl. Phys. 71 (1992), p. 3962-3965

[9] T. Ullmann, R. Jemmali and S. Hofmann: "*Non-Destructive Evaluation Methods for CMC Components*", Proc. ICACC-2009, Daytona Beach, FL (USA), on CD (2009)

[10] L. Chatzigeorgiou, M. Feiler and R. Aoki: "*Feasibility Study for Process Monitoring on Vacuum Infiltration Processes with Lock-in Thermography*", (in German), German Soc. of Non-Destructive Testing, DGZfP Berichtsband 86-CD, p. 83-90 (2003)

[11] D. Döring, F. Siegmund, M. Rheinfurth, I. Solodov, G. Busse and E. Haberstroh: "*Air-Coupled Ultrasonic Lamb Waves for Process Monitoring*", Online-Proc. 10th Europ. Conf. on Non-Destructive Testing – ECNDT, 1.03.50 (2010). http://www.ndt.net/article/ecndt2010/reports/1_03_50.pdf

[12] T. Ullmann, R. Jemmali, S. Hofmann, T. Reimer, C. Zuber, K. Stubicar and H. Weihs: "*Computed Tomography for Non-Destructive Inspection of Hot Structures and TPS Components*", Proc. 6th Europ. Workshop on Thermal Protection Systems and Hot Struktures, Stuttgart (Germany), on CD (2009)