NDT of free formed CFRP composites with laser ultrasonic

Oliver Focke, Michael Kalms, Christoph v. Kopylow, Werner Jueptner

BIAS – Bremen Institute of Applied Beam Technology,
28359 Bremen, Klagenfurter Str. 2, Germany

ABSTRACT

In recent years the use of carbon fiber reinforced plastics (CFRP) in manufacturing of aircraft and auto cars has increased continually. These materials are of interest because of their excellent mechanical properties like high strength and stiffness at low weight. In consequence of the development of new production processes machine-made CFRP components became more complex in design and shape.

The automatic inspection of high quantities of different complex shaped parts is a big challenge for the NDT industry. Especially the examination of free formed composites requires the adaptation of existing equipment or the development of new inspection tools. One new approach for a flexible tool for the investigation of free form CFRP components is laser based ultrasound. This technique has the advantage of being independent from the contour of the component under investigation. The main difference to the well known conventional ultrasonic inspection technique is the substitution of the piezoelectric transducer by two lasers, one for the generation and the other one for the detection of the ultrasound waves. The use of these laser systems enables an inspection without a couplant and with no contact to the component under investigation. In addition this configuration works from greater distances to the objects surface and therefore allows the inspection of structures with difficult access.

1 Introduction

Composite materials like CFRP become more important in the design and manufacturing of aircraft structures. This is because of the properties of these materials like good rigidity, high strength, low density, corrosion resistance, vibration resistance and low thermal expansion. The tensile strength of a single carbon fibre is anisotropic. This means, it is different along the fibre and perpendicular to it. Hence CFRP parts have to be designed in a way corresponding to the load during use of the component. Different configurations of each layer direction for ex. like 45°/45° or woven fabric inlays can be designed.

The industrial production of shaped composites in higher quantities is a challenge for the corresponding measurement and testing procedures as well. Techniques are required which are able to investigate these parts. A well-established testing tool is conventional ultrasound. It is used for detecting flaws in the material like cracks, disbondings or delaminations and it is also used to appoint material characteristics like the Young's modulus. But the increasing complexity of composites makes the automated and even the manual inspection difficult when using standard piezoelectric transducers. As an example for such a component which cannot be inspected easily the formed component in Fig.1 is shown. The requirement of conventional water-coupled transducers to remain within a few degrees to the surface normal cannot be fulfilled in all positions of this component.

Laser ultrasound combines the capability of conventional ultrasound to detect the above mentioned flaws with some advantages[1]. It is a non contact method, the operating distance can be up to several meters, no couplant is required and it is able to inspect at different angles of the incident beam to the surface normal and therefore no information about the shape of the inspected part is required. Hence the technique is almost insensitive to the orientation of the surface.

Fig.1: *12mm thick complex formed composite.*

1.1 Principle of Laser Ultrasound

Laser ultrasound works with two laser beams which interact with the surface of the inspected object. Instead of a piezoelectric transducer, which can act as a transmitter and a receiver, the laser systems are used for generating and probing elastic waves at the surface.

A short pulse laser is used for the generation and a long pulse or a continuous wave laser is used for the detection of the ultrasound waves. The generation process depends on the laser energy, the laser pulse length, the thermal conductivity of the material and the optical penetration depth of the wavelength into the component.

The generated ultrasound waves are propagating through the object under investigation and are reflected at the rear side or at discontinuities within the material. The motion of the surface, caused by the returning ultrasound wave, causes a frequency shift on the backscattered light of the detection laser. To demodulate this Doppler-shift of the frequency of the reflected light an interferometer is used. Afterwards the optical signal will be transformed into an electrical signal which describes the surface motion equivalent to the measurement signal of conventional ultrasound systems and can be displayed by an oscilloscope. In Fig.2 an impulse-echo-setup is shown where both laser beams are pointing at the same spot on the surface of the inspected component. The backscattered light is collected by optics and brought via an optical fiber to an interferometer. The ultrasound signal is displayed by an oscilloscope.

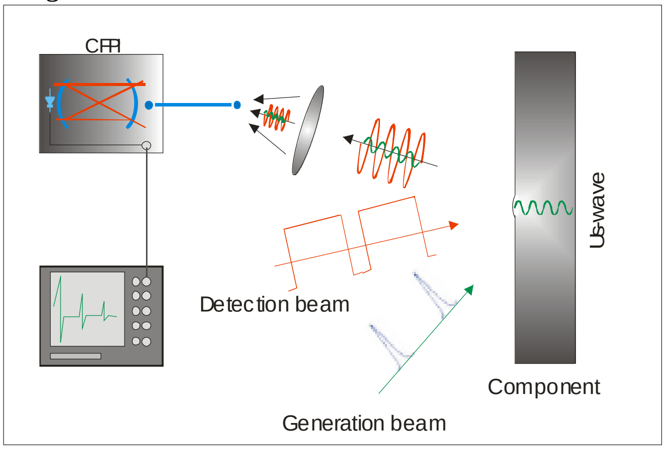


Fig.2*: Principle of the laser ultrasound technique.*

1.2 Generation

For the generation of ultrasound waves two different regimes can be distinguished: The nondestructive thermo elastic- and the ablative regime.

When the power of the laser pulse exceeds a certain level, surface material is vaporized. The recoil of the ablated particles generates a longitudinal wave which is propagating mainly perpendicular through the inspected component (Fig.3). When the pulse power does not achieve this level the ultrasound generation is based on the thermo elastic effect. Thereby the laser light penetrates to some extent below the surface of the material, is absorbed and generates stress caused by the thermal expansion. This stress is then transformed into ultrasound surface- and bulk- (shear- and longitudinal-) waves. The proportion of surface- to bulk waves depends on the deepness of the ultrasound source in the material which is affected by the optical penetration depth and the thermal conductivity of the material [2, 3, 4, 5, 6]. In addition the depth of the ultrasound source influences the propagation direction of the bulk waves.

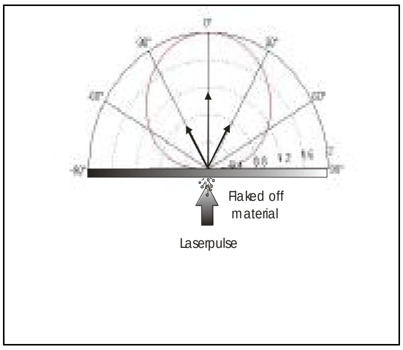


Fig.3: *Ablative laser ultrasound generation: The recoil of the particles flaking off from the surface generates a longitudinal wave perpendicular to the surface.*

First investigations on laser ultrasound were made in [7] where a Nd:YAG laser generates ultrasound waves in metals. There the dimension of the ultrasound source depends more on the size of the laser spot than of the optical penetration depth into the material. This is due to the fact that the absorption and reflection of the Nd:YAG laser radiation take place within a few nanometers[8] near the surface and this is mainly an interaction of the incident beam with the conduction-band electrons. The induced motion of these electrons heats the illuminated region causing stress in this surface layer.

This stress is predominant parallel to the surface. Normal strains are low since there is not enough material over the heated region to translate the expansion into an impulse into the material. Therefore most of the energy will be transformed into surface waves. The typical sound field of a so called surface absorber is shown in Fig.4 on the left side. The main direction of the longitudinal wave is 60°. Only a small amount is transformed into longitudinal waves which are propagating perpendicular to the surface through the component. Due to the fact that metals have a high thermal conductivity the ultrasound source has an extension inside of the inspected part.

For the inspection in the thermo elastic regime where the optical penetration depth of the material is only a few nm the surface inspection is predominant. Applications can be found for example in the inspection of metal- or paper-sheets by exciting lamb waves[9].

Fig.4: *Sound field characteristic for different absorbers: Surface- (left) and volume- absorber (right).*

To generate longitudinal waves in metals perpendicular to the surface the ablative regime has to be used. A more detailed description is given in [10]. An application as a testing tool can be found in the tube industry where the wall thickness of heated tubes is of interest[11]. The small amount of material which is vaporized has no influences on the functionality of the tubes.

For the generation of compressive waves perpendicular to the surface in other materials than surface absorbers, the ultrasound generating volume must have a depth of several µm. Hence it is necessary to adapt the wavelength to the absorption of the material. For CFRP a wavelength of 10µm, that can be generated by a CO_2-laser, is suitable because it has a penetration depth of about 30µm in the resin. Here the stress distribution can be represented by an ensemble of buried thermo elastic point sources with decreasing size because the light intensity goes down in value while transmitting through the material. The consequence is normal stress to the surface. This stress implicates a longitudinal ultrasound wave which is propagating perpendicular to the surface through the component. This means an existing buried ultrasound source generates a sound field as shown in Fig.4 even when the direction of the incident generation laser beam is not normal to the surface.

This characteristic of the ultrasound generation allows a measurement setup that is nearly independent from the orientation of the object to the incident laser beam. Hence the generation laser can be scanned over the surface with the help of a mirror without considering the shape or position of the test object. The generated ultrasound wave is always perpendicular to the surface. This is due to the fact that the surface itself is the source of the generated ultrasound waves.
The ultrasound frequencies which are generated by a laser source should be in the same range as used in the conventional ultrasound testing. To realize this, the induced thermo elastic expansion has to be short in time.
The frequency of the ultrasound wave depends on the pulse length of the laser, the optical penetration depth into the material and the thermal conductivity.

For example a CO_2 laser with a pulse length of 70nsec will generate in CFRP components elastic waves with a frequency bandwidth in the range of 1 to 10 MHz.

1.3 Detection

In difference to the generation laser the wavelength of the detection laser is characterised by having only one single longitudinal mode with small line width. To detect a sequence of ultrasound echoes, the pulse duration has to longer than the runtime of the ultrasound wave in the object. A pulse duration in the range of several microseconds or the use of cw-lasers is therefore necessary.

Ultrasound waves underlie a material specific absorption while passing through the component and are reflected at the back side or at flaws. Returned to the front side they excite a surface displacement in the range of few nanometres which generates a frequency shift on the backscattered laser beam by the Doppler-effect. This light is collected by optics and transported via an optical fibre to an interferometer. Very often a confocal Fabry-Perot interferometer (CFPI) is used. This CFPI is stabilized on the frequency of the detection laser so that the laser frequency strikes the rising or falling edge of the transmission peak of the CFPI. The frequency modulation due to the ultrasound wave generates an intensity modulation behind the CFPI that can be detected The free spectral range (FSR) and the finesse of the CFPI are adapted in the way that the typical ultrasound frequencies generated in the CFRP (1-10MHz) can be detected.

2 Experimental Setup

The setup of the laser ultrasound system is shown in Fig.5 where the detection laser (Nd:YAG) is placed on the top of the generation laser (TEA-CO_2).

Fig.5*: Beam propagation of the system (red line CO_2-laser, blue line Nd:YAG laser).*

The optical setup consists of several components to combine the TEA-CO_2- and the Nd:YAG laser beam collinear. The parameters of both beams are adapted to reach a maximum operating range for the system. The operating range is about 250mm without any auto focus system. The test object can be fixed on a translation stage to allow surface scans.

2.1 TEA-CO_2-Laser

For the laser based generation of ultrasound waves in CFRP a Transversaly Excited Atmoshperic Pressure Laser (TEA) based on CO_2 is used. This special configuration allows higher pressure of more than 1 bar and a pulsed gas discharge with pulse durations of about 1 µs, Pulse energies of several kJ and pulse lengths between 0,1 – 0,5 µs can be achieved. The beam of the pulsed TEA-CO_2-laser has to be optimized in pulse length, pulse energy and pulse amplitude. For the TEA-CO_2-laser these properties depend on the gas discharge in the cavity, the gas pressure, the gas mixture and the reflectivity of the output coupler. To select the optical wavelength of 10,64µm an aperture had to be positioned in the optical path of the cavity. The laser pulse consists of a main pulse and a tail. For optimum use it is necessary to suppress the typical tail of a CO_2-laserpulse by reducing the amount of N_2 in the gas mixture, because this part of the gas mixture transfers energy from the N_2–molecules to the CO_2-molecules. The tail has no influence on the generation of the ultrasound; in contrast it is only heating the inspected component. The optimized pulse is shown in Fig.6. The main pulse is produced by direct pumping of the laser niveaus in the gas discharge. Because of the Doppler-broadening of the laser line due to the high pressure, mode coupling is possible and leads to pulse durations of 100 ns. This pulse length is an optimum for the generation of ultrasound in carbon fibre materials.

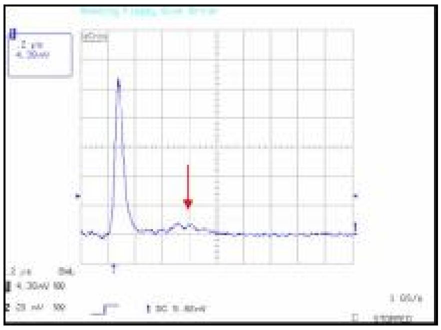


Fig.6: *Modified TEA-CO_2-laser pulse.*

2.2 Nd:YAG Long Pulse Laser

Since a CFRP component has poor reflectivity properties at the wavelength of 1,06µm, a strong detection laser is necessary in order to obtain enough light reflected from the surface.

The use of a high power cw-laser is not reasonable if the measuring time is in the range of microseconds and the repetition rate is about 100 Hz. Most light energy is absorbed unused from the component and damage could occur. To keep the deposited energy low a pulsed laser with a pulse length in the range of a few microseconds is a solution.

A laser system which is able to generate a pulse length of 70µsec with a high peak power from 1,2kW is shown in Fig.7. A diode pumped single frequency cw-laser of 1,2W and a wavelength of 1,064µm is taken as seed laser. The linewidth of this laser is only a few kHz, what is noticeable smaller than the Airy-modes of the interferometer and therefore sufficient for the use in combination with it. The laser beam is guided through three amplifiers. The first amplifier consists of two flash lamps, each of the second and the third have one flash lamp installed. The flashlamp discharges inside the amplifiers are timed in such a way that the seed laser beam has a 70µsec long pulse length. To keep the linewidth low, Pockel-cells are used to time the discharge and to prevent spontaneous emission. To avoid light propagating back into the seed laser optical diodes are used. The system delivers a light beam which is characterised by single frequency operation with a small linewidth and low amplitude noise in combination with high output power.

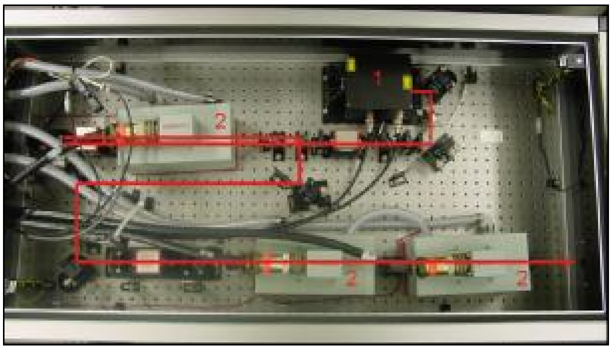


Fig.7: *The Nd:YAG detection laser. The seed laser is marked with 1, the three amplifiers are marked with 2.*

2.3 Confocal Fabry-Perot Interferometer

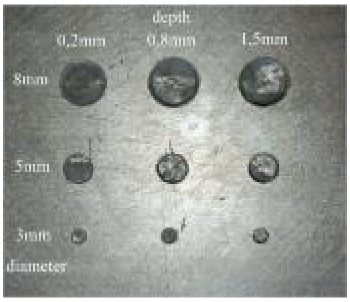
The confocal Fabry-Perot interferometer is connected with a fibre to the collecting optics. The finesse is chosen in the way, that frequency modulations of the detection laser in the range of 500kHz up to 140MHz can be detected in the transmission mode. The free spectral range of the 50cm long cavity is 150MHz. Low frequency drifts by the detection laser are compensated by stabilization of the resonator length of the confocal Fabry-Perot interferometer on the detection laser.

3 Experimental Results

The laser ultrasound investigations were made in cooperation with Airbus Germany (NDT-Group Bremen).

To demonstrate the capability of the system, samples with typical defects have been generated. The selection of inspected components varies from flat composites over lightly shaped to complex formed geometries. For flaw simulation flat-bottom holes with different drill diameter and depth are implanted. Porosity in composites parts will also be verified.

The first sample is a 4,6mm thick plane CFRP component. The manipulated back side of the sample is shown in Fig.8. Flat bottom holes with different depth and diameter are inserted, the sizes are sketched in the image. The depths of the simulated flaws are varying between 0,2mm and 1,5mm and the diameter from 3mm to 8mm. The measured field is 60mm x 60mm. In the C-Scan the colours are indicating the different running times for the returned ultrasound waves. A scale is shown which indicates the colour to the running time in µsec. As shown in the time of flight scan all flat-bottom holes have been found.



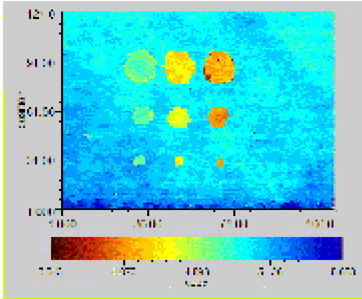


Fig.8: *Test component with holes. Left: backside of the component. Right: time of flight scan with scale.*

Fig.9 displays a 4mm thick fabric composite plate with pores. The pores were first found with a conventional ultrasound system in an immersion technique, the areas were then marked white. In the amplitude D-scan, done with the laser ultrasound system, the detected pores can be seen as brown till dark blue areas. The woven structure of the sample can be identified by the diagonal dotted yellow line in the scan.

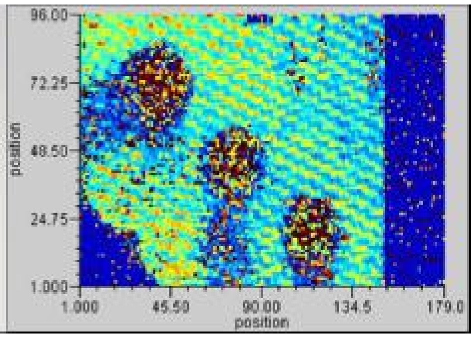
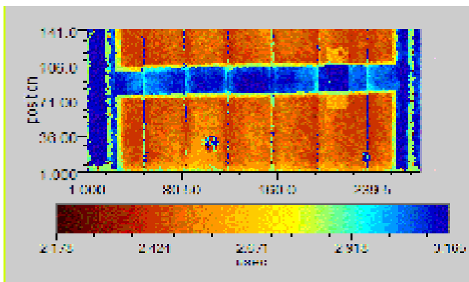


Fig.9a: *Photo of the 4mm thick CFRP.* Fig.9b: *C-Scan obtained with laser ultrasound.*

In Fig.13 a slight curved component out of the fuselage area with unequal thickness and stringers is displayed. On the right side the C- and D-scans of a 500mm x 200mm large area, obtained with the laser ultrasound system, is shown. The photograph illustrates the rear side of the component with the inserted two defects which are marked with squares. These defects act as delaminations in the unidirectional set up of the component. The sticker is applied onto the backside in a way that different layer thicknesses are covered.

In the time of flight scan the stringer and the different layer thicknesses, varying between 1,2mm to 2mm, can be identified by dissimilar colours which express unequal arrival times. Even the stepwise heightening of the layer thickness can be verified as the colour is changing from green over yellow to brown. A similar result shows the C-scan on the bottom right side in Fig.10 where the amplitude of the ultrasound wave is analysed.

In the C- and as well in the D-scan both delaminations can be identified as a change in the amplitude and in the arrival time of the ultrasound wave. Also the 80µm thick sticker affects the amplitude and the running time of the ultrasound wave.



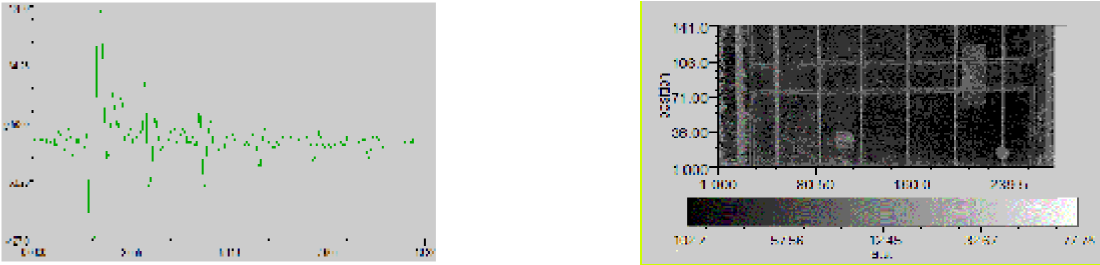


Fig.10: *Top left: backside of the lightly formed component with inserted flaws and a sticker. The measured area is 500mm x 200mm large. The thickness is varying from 1,2mm – 2mm. Top right: Time of flight scan below the c-scan.*

The component shown in Fig.13 is characterised by a rough surface which makes an investigation under big angles easy because the light is scattered uniformly. Also because the part has an unidirectional setup less absorption of the ultrasound amplitude occurs. In addition with a thickness of 1,2mm to 2mm the part is quite thin which results in a sequence of up to five back wall echoes that can clearly be seen in the A-Scan (Fig.11 bottom left).

The performance of the laser ultrasound technology and the testing system during the measurement of strongly shaped components is illustrated in Fig.11. At the top left side the view from the detection optics to the composite is shown, the inspected area is marked. The component is in a fixed position with the flat sides having an angle of 45° to the optical axes of the detection optics. The part is mounted on an x-y translation stage, which has a moving direction perpendicular to the optical path of the generation and detection laser beam. The inspection is done in one single scan whereby the lower back reflection of the flat side of the inspected part caused by the inspection angle is compensated by the electronically controlled dielectric mirror which was introduced earlier. On the right side of Fig.11 a photo of the components backside with the inserted flat bottom holes is shown. Five generated flaws are situated in the region of the radius, two are located on the flat side. Each flaw is marked with the size of its diameter.

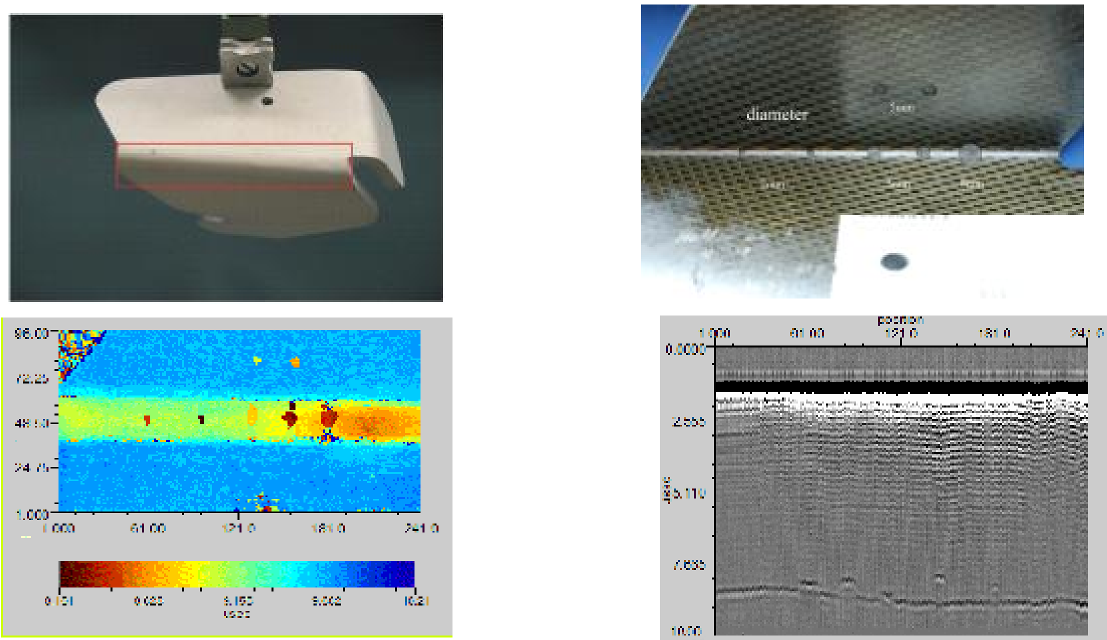


Fig.11: *Top: View from the detection optics onto the shaped part. Top right: Rear side with inserted flaws. Bottom left: Time of flight C-scan. Bottom right: B-scan out of the area of curvature.*

In the bottom left side the result of the inspection in a time of flight scan is illustrated. All flaws are identified - the five flaws in the radius as well as the flaws on the flat side. Beside the unequal depth of the inserted drilling holes also the thickness along the area of curvature varies. This can be seen in a b-scan which was taken along the radius.

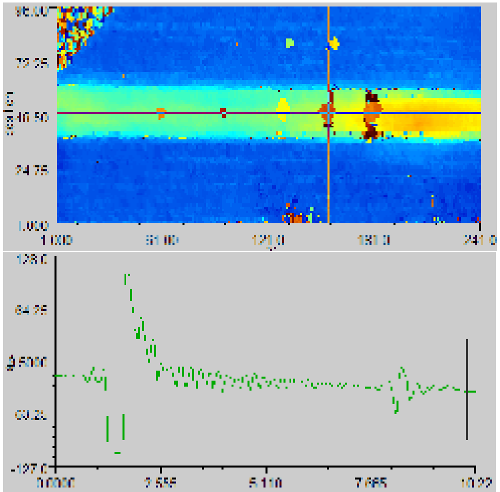


Fig.12: *Time of flight scan with the corresponding A-Scan including the measuring window.*

Exemplarily two A-scans out of the regions with drilling holes are shown. The positions of the A-scans are indicated by the cross in the belonging C-Scan. Considering the material specific velocity of an ultrasound wave in the CFRP component a thickness difference of 750µm, between the drilling holes can be specified. By comparing the running time of the back wall echo in the left side

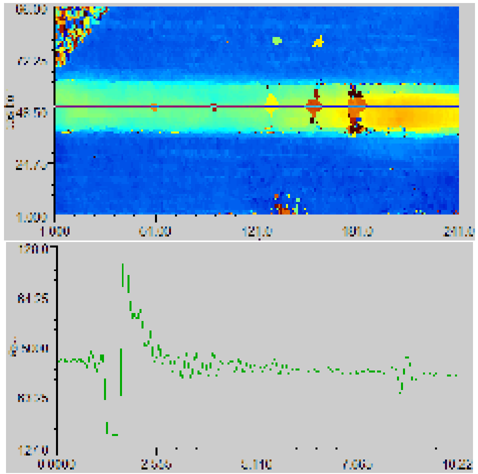


Fig.13: *Time of flight scan with the corresponding A-Scan including the measuring window.*

4 Summary

A pulse-echo laser ultrasound system was described that allows the inspection of free formed carbon fibre reinforced plastics. The use of this system was demonstrated on parts of various shapes, thicknesses and compositions. Flaws with different sizes could be verified. In addition it is possible to make a full scan of the strongly shaped part without facing any problem.

The authors wish to express their thanks to Airbus Germany. Exceptionally should be mentioned the very good cooperation with Wolfgang Bisle, Rudolf Henrich and Soenke Seebacher (all Airbus Germany NDT Group Bremen).

5 References

[1] J. P. Monchalin, P. Bouchard, et.al. –Laser-ultrasonics: from the laboratory to the shop floor, *Advanced Performance Materials*, Vol. 5, No. 1-2, 1998, pp. 7-23(17).

[2] L. R. F. Rose – Point-source Representation for Lasergenerated Ultrasound, *J. Acoust. Soc. Am* 75 , 1984, pp. 723.

[3] U. Schleichert – Die Theorie der optischen Erzeugung elastischer Wellen in Festkörpern, Dissertation, University Kassel, Kassel, 1989.

[4] R. J. Conant, K. L. Telschow, – Optical and thermal parameter effects on laser generated ultrasound, *J. Acoust. Soc. Am.*, Vol. 88 No.3, 1990.

[5] R. J. Conant, K. L. Telschow, – Longitudinal wave precursor signal from an optically penetrating thermoelastic laser source, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 8A , 1989, pp. 497-504.

[6] P. A. Doyle, – On epicentral waveforms for laser generated ultrasound, *J. Phys. D: Appl. Phys.*, Vol. 19, 1986, pp. 1613.

[7] R. M. White – Generation of Elastic Waves by Transient Surface Heating, *J. Appl. Phys.*34, 1963, pp. 3559.

[8] C. Scruby, L. Drain – *Laser Ultrasonics: Techniques and Application*, Chapter 5 Adam Hilger, Bristol UK, 1990.

[9] M. A. Johnson, V. H. Bertheolot, P. H. Brodeur, L.A. Jacobs – Investigation of laser generation of Lamb waves in copy paper, *Ultrasonics* 34, 1996, pp. 703-710.

[10] A. Hofmann, – Optische Erzeugung von Ultraschall durch Materialablation, Dissertation Saarbrücken , 1998.

[11] M. Paul – Wandstärkemessung im Rohrwalzwerk mittels Laserultraschall, Dissertation, Universität des Saarlandes, Saarbrücken, 1998.