1 Introduction and Objectives

Composite materials are gaining increasing importance in the aerospace and automotive industries due to their advantages in weight, stiffness, and strength. The CFRP-structural weight content increased from below 40% in case of the A380 to about 50% for the Airbus A350 and the Boeing 787. Due to high safety requirements in the use of these materials in primary and secondary aircraft structures, composite materials demand sophisticated testing methods such as ultrasonic inspection, X-ray, computer tomography, or thermography. With regard to the shape and dimension of aircraft parts in combination with resolution and inspection time not bottlenecking the throughput, only ultrasonic testing (UT) in particular provides excellent results for the reliable detection of a broad variety of defects. Therefore, many publications can be found in literature giving further information about improvements in this technique. However, most of these publications deal with lamb waves or with phased-array-techniques [1 – 5], but none can be found in the field of double through-transmission technique.

Little attention in terms of nondestructive inspection is paid to new developments in the field of tension-compression struts for supporting aircraft structures. Being an aluminum part for decades, struts built in the A380 and A350 are designed to be filament wound CFRP-rods with lengths between 300 – 1200 mm and diameters between 15 and 36 mm. The wall thicknesses vary between 1.25 and 5 mm. In general, the inspection of aircraft parts has to be in accordance with the standards of aircraft companies. In terms of Airbus Industries, these standards are called AITM’s, which is the abbreviation for Airbus Industries Test Method. Since Airbus Industries has a long tradition of manufacturing shell-like CFRP-components and no tradition to either produce or to utilize filament wound parts, no AITM-standards are applicable. In addition, it is obvious that by dealing with some thousand struts annually, manually performed test procedures are out of question. Thus, the following objectives were defined:

- Development of a suitable UT-method
- Selection of an optimal transducer
- Definition of the acceptance limit and the acceptable defect size

2 Equipment

2.1 Ultrasonic Facility

The research and development described was conducted at the Institut für Kunststofftechnik Westpfalz (IKW) located on the campus of the University of Applied Sciences Kaiserslautern. The institute’s state-of-the-art ultrasonic system was manufactured by the company Hillger in Germany and operates in a frequency range from 0.1 up to 30 MHz in a fully digitized way. Ultrasound can be applied water- and air-coupled. However, in this study only water coupling was used. The Hillger-software package allows the realization of through-transmission tests and A-, B-, C-, D-, and F-scans, which e.g. allows the evaluation of frequency shift based on real-time Fast-Fourier-Transformation (FFT). In addition, full-waveform-scans can be performed allowing post-scanning gate-settings. In total, besides a trigger gate two evaluation gates can be set. Three scanning systems can be connected to the ultrasonic control unit:

- Four axes system for shell-like parts (40 x 60 x 80 cm) and short rotational parts
- Two axes system for rotational parts (length 120 cm, diameter 15 cm)
• Two axes system for through-transmission air-coupled ultrasonic testing.

2.2 Transducers

All transducers were manufactured by Olympus NDT – Panametrics. The transducer properties are listed in Table 1. The near field length \( N \) (in water) mentioned in Table 1 can be calculated according to Eqn. 1:

\[
N = \frac{D^2}{4 \lambda_{H,0}}
\]  

(1)

where \( D \) is the diameter of the active element and \( \lambda \) is the wave length in water. The minimum bundle diameter \( b \) of the focused ultrasound can be calculated with a 6 dB threshold as follows [6]:

\[
b_{6\text{dB}} = 0.26 \frac{FD}{N}
\]  

(2)

with \( F \) being the focal length (point target focus - PTF) of the transducer.

2.3 Samples

Two different CFRP-cylinders were produced in a filament winding process. Sample 1 possessed an outer diameter of 40 mm and a wall thickness of 5 mm. Holes in axial direction were drilled with diameters of 0.7, 1, and 2 mm in different distances (25% = high, 50% = middle and 75% = low of thickness) from the top as depicted in Fig. 1a.

Sample 2 had a diameter of 45 mm with a wall thickness of 2.5 mm. Holes in axial direction were drilled with diameters of 0.5, 0.7, and 1 mm also in different distances (25%, 50% and 75% of thickness) from the top. In addition, boreholes with diameters of 1.3, 1.6, and 2 mm were drilled in 50% wall thickness. The angle between the boreholes was always 30°. All drillings were done up to a depth of at least 10 mm which was the limit for 0.5 mm drill used in CFRP (Fig. 1b).

### Table 1: Transducer properties

<table>
<thead>
<tr>
<th>Transducer name</th>
<th>Frequency ( f ) [MHz]</th>
<th>Diameter of active element ( D ) [inch]</th>
<th>Focal length ( F ) [mm]</th>
<th>Near field length ( N ) [mm]</th>
<th>Bundle diameter ( b ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>V389</td>
<td>0.5</td>
<td>1.5</td>
<td>96.5</td>
<td>122</td>
<td>7.87</td>
</tr>
<tr>
<td>V394</td>
<td>1</td>
<td>1.125</td>
<td>96.5</td>
<td>137</td>
<td>5.25</td>
</tr>
<tr>
<td>V304</td>
<td>2.25</td>
<td>1</td>
<td>76.2</td>
<td>244</td>
<td>2.07</td>
</tr>
<tr>
<td>V309</td>
<td>5</td>
<td>0.5</td>
<td>50.8</td>
<td>136</td>
<td>1.24</td>
</tr>
<tr>
<td>V311</td>
<td>10</td>
<td>0.5</td>
<td>30</td>
<td>271</td>
<td>0.37</td>
</tr>
<tr>
<td>V313</td>
<td>15</td>
<td>0.25</td>
<td>50.8</td>
<td>102</td>
<td>0.83</td>
</tr>
<tr>
<td>V324</td>
<td>25</td>
<td>0.25</td>
<td>12.7</td>
<td>169</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Fig 1a: Composition of boreholes in sample 1

Fig 1b: Composition of boreholes in sample 2

3 Methodology of Ultrasonic Testing

3.1 Testing Techniques

Ultrasonic testing can be performed by means of three different techniques:

• Pulse-echo technique
• Through-transmission
• Double through-transmission technique
Pulse-echo and double through-transmission require only one transducer, whereas through-transmission needs two transducers on each side of the part. Thus, in terms of thin rotational parts, through-transmission is not suitable, because two walls are tested simultaneously. Pulse-echo and double through-transmission testing can be performed simultaneously with one gate covering either defect echo or back-surface echo and the other gate set around the echo from the auxiliary reflector.

### 3.2 Transducer Selection

The selection of the transducer shall be done according to the maximal achievable signal/noise ratio (SNR) [7]. The ultrasonic wavelength in terms of the evaluation of auxiliary reflector echoes when testing thin-walled parts does not matter so much as for pulse-echo measurements. Thus, also low frequency transducers can be applied. However, the imaging of the defect size has to be precise in terms of acceptable defect size.

### 4 Ultrasonic Testing

The transducers described in Table 1 were used for ultrasonic testing of the samples introduced. Sample 1 was inspected with a diameter of the auxiliary reflector of 25 mm, whereas the measurements with sample 2 were performed with two different auxiliary reflectors with diameters of 25 and 36 mm (Fig. 2). A segment with a height of 25 mm was scanned with an increment of 0.1 mm in axial direction and 0.3° in rotary direction. In terms of sample 1, the focus point set on the sample surface (SSR) and on the surface of the auxiliary reflector (ASR) for testing frequencies higher than 2.25 MHz, whereas for the inspection of sample 2, it was focused on the sample surface.

For the evaluation of the back-surface, a gate with a width of 1 µs was set around the back-surface echo (BSE). The same procedure was conducted for the auxiliary reflector echo (ARE).

### 5 Results

It turned out that the 0.5 MHz and the 25 MHz transducer were not able to detect any borehole in neither sample 1 nor sample 2. Thus, they were excluded from later evaluations. Fig. 3a shows exemplarily a C-scan evaluating the auxiliary reflector echo of sample 1 performed with the 2.25 MHz-transducer.

The white zone at the right side was caused by a calibration mark. All boreholes were detected (starting from the calibration mark: 2 mm low, middle, high, same for 1 and 0.7 mm). The 0.7 mm boreholes with a diameter slightly above half of the
average wavelength of 1.2 mm (c_{CFRP} = 2,600 m/s) could be detected.

Fig. 3b depicts the result of sample 1 scanned with 2.25 MHz but in contrary to Fig. 3a, with the gate set around the back-surface echo.

It can be seen that 0.7 mm boreholes closer to the back-surface were suboptimally detected. In terms of higher frequencies (e.g. 10 MHz) the imaging of boreholes is much sharper. Due to the average wavelength of 0.26 mm, all defects were found (Fig. 4a).

The scan evaluating the back-surface echo shows similar results as in Fig. 3b. The boreholes with 0.7 mm are not well visible in comparison to the ARE-measurement (Fig. 4b).

In comparison, the scan of sample 2 is depicted in Fig. 5a.

Starting from the calibration mark at the right side, the 2 mm, 1.7 mm, and 1.3 mm borehole are clearly visible. Indications of the smaller boreholes in different depths can be noted. However, the shape representation is not very exact. The C-scan of sample 2 corresponding to the back-surface echo evaluation displays a much sharper defects representation (Fig. 5b). Nevertheless, defects close to the back-surface are hardly visible. The images of Fig. 5a and 5b are representative for sample 2.

6 Evaluation

6.1 Fundamentals

The signal/noise ratio determines how much the echo amplitude of an indication differs from that of the flawless vicinity. In order to quantify the signal/noise ratio of an indication, four different approaches can be realized;

a. maximum indication amplitude versus maximum ambient echo
b. maximum indication amplitude versus average ambient echo
c. average indication amplitude versus maximum ambient echo
d. average indication amplitude versus average ambient echo,

where the ambient can be understood as that part of the sample not including any defects. The echoes influenced by the boreholes were not homogeneously distributed as seen in Fig. 3 – 5. The same can be stated for the echoes of the flawless regions between the indications. Thus, the maximum indication amplitude versus maximum ambient echo was used for the analysis of the signal/noise ratio. This procedure is also consistent with the optical assessment strategy of an UT-operator to identify an indication by looking at the highest difference between indication and ambient echo amplitudes (sharpest contrast). Parameters significantly influencing the signal/noise ratio are as follows:
• depths of defect
• defect size
• transducer frequency
• focal length
• bundle diameter (focal point diameter)
• active element diameter
• inspection strategy (kind of echo, position of focal point)

Focal length, focal point diameter, active element diameter and frequency are transducer properties and cannot be chosen freely [7]. Due to the thin walls of composite materials, 50 mm (2”) are in most cases a suitable focal length. However, these parameters are not independent and thus just the frequency was varied for this study. The influence of the remaining four parameters was analyzed by keeping two of them constant and considering the effect of variations of the two others on the signal/noise ratio.

6.2 Influence of Borehole Diameter

6.2.1 Sample 1

First, the dependency of the borehole diameter was evaluated. The result of this evaluation can be seen in Fig. 6a and 6b for sample 1 and two different focal point positions.

Fig. 6a: Signal/noise ratio depending on borehole diameter of sample 1 (middle borehole, ARE)

Fig. 6a and 6b show that the signal/noise ratio increases with an increase in borehole diameter. Due to its long wavelength, the 1 MHz transducer was able to detect just the largest hole. The higher transducer frequencies (10 MHz and 15 MHz) provides higher signal/noise ratios for the smaller holes whereas the 5 MHz transducer leads to better results for the largest borehole of 2 mm.

Fig. 6b: Signal/noise ratio depending on borehole diameter of sample 1 (middle borehole, BSE)

Furthermore, it can be stated that the influence of the focal point position is negligible. The signal/noise ratio for the 0.7 mm borehole is higher in case of the evaluation of the back-surface echo in comparison to the auxiliary reflector echo. In terms of the 2 mm hole, it is vice versa. Regarding the 1 mm hole, the higher frequencies provide higher signal/noise ratios for the back-surface echo. Lower frequencies cause higher signal/noise ratios for the auxiliary reflector echo.

6.2.2 Sample 2

In Fig. 7a and 7b, the signal/noise ratios of sample 2 and the two different auxiliary reflectors are depicted. It can be seen in both figures that the signal/noise ratio increases with an increase in borehole diameter and is highest for the 5 MHz and the 10 MHz transducers. No indications were found using the 1 MHz transducer and the thicker auxiliary reflector due to impacts of the back-surface echo on the auxiliary reflector echo. This impact did not exist in case of the thinner reflector having a larger water path distance and thus better damping to echoes coming from the inner sample surface. However, for higher frequencies no strong influence of the reflector diameter on the signal/noise ratio can be noticed.

Comparing both figures, it can be noted that the trends are very similar. In terms of using a 5 MHz or
CORRELATION OF TRANSDUCER FREQUENCY AND SIGNAL/NOISE RATIO OF THIN WALLED FILAMENT WOUND CFRP-TUBES INSPECTED BY ULTRASONICS

10 MHz, it makes no difference which reflector was utilized.

Fig. 7a: Signal/noise ratio depending on borehole diameter of sample 2 (middle borehole, ARE, 36 mm reflector)

Fig. 7b: Signal/noise ratio depending on borehole diameter of sample 2 (middle borehole, ARE, 25 mm reflector)

Fig. 7c images the signal/noise ratio of sample 2 with regard to the back-surface echo. The 10 MHz probe produces the highest signal/noise ratio followed by the 15 MHz and the 5 MHz transducer. This is on the one hand caused by a better damping of the 10 MHz transducer in comparison to the 5 MHz transducer reducing the intensity of post-oscillations of the front surface echo. On the other hand, ultrasound of the 15 MHz is attenuated to a very high amount leading to a decrease of the back-surface echo. The 0.5 mm borehole could not be detected. The 0.7 mm borehole was found only by means of the 10 MHz probe.

6.3 Influence of Borehole Diameter

6.3.1 Sample 1

Fig. 8a displays the influence of the borehole position on the signal/noise ratio for various frequencies. It is obvious for all frequencies that in terms of monitoring the back-surface echo the borehole close to it ("low"-position) is detected with a reduced signal/noise ratio. This can be explained by a partial compensation of the reduction of the back-surface echo by impacts from the hole-echo.

Fig. 7c: Signal/noise ratio depending on borehole diameter of sample 2 (middle borehole, BSE)

6.3.2 Sample 2

Fig. 8b shows also the influence of the borehole position on the signal/noise ratio for various frequencies. Due to the thin wall thickness, it was not possible to detect boreholes close to the back-surface when evaluating the back-surface echo.
6.4 Influence of Transducer Frequency

Fig. 9 depicts that the signal/noise ratio depends on the transducer frequency having a maximum at 5 MHz. However, it has to be taken into account that according to Table 1 the transducers used have also different bundle diameters (often called focal point diameter) of their focused ultrasound larger than the diameter of the boreholes resulting in ultrasound passing the hole without any reflection. Furthermore, it can be stated that in most cases the signal/noise ratio coming from the back-surface echo evaluation is lower than for the auxiliary reflector based measurement. An exception is made by the 10 MHz transducer due to its much shorter focal length and very small bundle diameter. This makes the transducer more sensitive to deviations from concentric revolutions.

7 Conclusions

The signal/noise ratio is significantly influenced by seven parameters, which are not independent of each other. Thus, it seems to be difficult to choose the optimal transducer providing the highest detectability of defects possible whereas the defects have certain size for a given material situation. However, the minimum defect size to be detected in Airbus CFRP-aircraft components is about 6 mm in diameter according to AITM-standards. This study dealt with smaller defects to show the limits of certain test frequencies and yielded that the 5 MHz transducer provides the highest signal/noise ratio as depicted in Fig. 9.

The comparison between the evaluation of a back-surface echo and an auxiliary reflector echo lead to the conclusion that monitoring the ARE provides in most cases a higher signal/noise ratio and more importantly facilitates a better detectability of defects close to the back-surface of the part under inspection. The choice of the diameter of the auxiliary reflector has to be done with care. If the diameter is too close to the inner diameter of the part, the un-damped amplitudes of the back-surface echo might interfere with the auxiliary reflector echo. However, if the diameter is too small, deviations from concentric revolutions might prevent the focused ultrasound to hit the top surface line causing oblique reflections and thus a reduction in signal/noise ratio. According to Fig. 7a and 7b a water path (distance between inner and outer surface) of 2 mm in case of a 5 MHz transducer seems to be sufficient. In addition, if applying such a water path, the adjustment of the focal point on either the front surface of the part under inspection
or the surface of the auxiliary reflector is not significant for the signal/noise ratio.

References


