Air Coupled Ultrasound - New approaches in the field of coupling agent-free testing

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Abstract
Air-coupled ultrasound testing methods are becoming more important each day. This is primarily due to the possibility of a “coupling agent-free” measurement and the associated benefits. Simultaneously, the equipment technology and the ultrasonic transducers continue to evolve. Air-coupled ultrasonic testing is predominantly used in process control in production chains and is ideally suited for testing materials and structures such as composites, adhesives and honeycomb structures. Thus, a wide range of inspection tasks such as interface detection, the exposure of inhomogeneities or the detection of foreign object inclusion can be covered. Our article is intended to give an overview of developments in the field of air-coupled ultrasonic testing and to present them using the example of specific test tasks. Two most popular techniques: through transmission and guided waves are presented and compared. Selected testing examples cover materials widely used in aerospace industry such as honeycomb sandwich structures, CFRP - aluminum compounds and more.

Keywords: ultrasonic, air-coupled, composites, honeycomb, delamination

1- Introduction
Air-coupled ultrasonic testing (ACUT) is an aerospace proven technology for inspecting CFRP-components. Based on continuous improvements in transducers technology, transmitting and receiving electronics and advanced evaluation algorithms, we have been working intensively on the development of new fields of application for air-coupled ultrasonic systems. These efforts are aimed in particular at testing high-damping materials as well as materials with multiple boundary layers of different properties. Even inspection tasks that could previously only be covered by conventional ultrasound, such as the testing of sheet metal welds, can now be partially replaced by air-coupled ultrasonic tests. (Compare [1])

Due to the need for lightweight construction in all areas of life, composite materials are rising in popularity. In the process of construction, the lightweight potential of the individual composite parts is increasingly being exploited. For this reason, the focus in quality control even with simple materials such as insulation sheets or sandwich structures is more placed on the structural integrity. The proof of the complete adhesion of cover layers to honeycomb cores and laminar bonds can be performed in the same way as the verification of the consolidation of pressed insulation boards. Delamination, air and foreign body inclusions as well as impact damage can be detected with the imaging air-coupled ultrasound technology. [1], [2]

The hybrid design, which is prevalent in many areas with a multi-material mix of metals, reinforced and unreinforced plastics as well as ceramics, is causing a change in the established joining technologies. Areal bonding is increasingly being used in these areas, posing new tasks for materials testing. A major challenge for non-destructive testing are "Kissing Bonds”, touching but non-adhesive areas in bonds. One approach to detect these flaws is the one-sided test in pitch / catch arrangement. (see [3], [4])

In the present article we will first discuss the test equipment used. This is followed by three examples of transmission testing and two examples of guided wave testing.

2- Measurement Equipment
The measurements in this article were performed using the High-End SONOAIR ACUT System. With four default input and output channels, this enables the operation of the SONOTEC Phased-Array ACUT transducers and the simultaneous measurement with four conventional transducers. Each channel allows a free configuration of the transmitter characteristics up to a voltage of 800 V. The combination of a preamplifier at the receiver and an internal amplifier in the electronics achieves an extremely low inherent noise of <1 nV / √Hz. The possible amplification dynamics of 120 dB is necessary to generate sufficient signal-to-noise ratio (SNR) for a meaningful and reproducible measurement even with highly attenuating materials. The excitation and detection of the air-coupled ultrasound is carried out with the CF series transducers listed in Table 1.
Table 1: Overview ACUT-Transducers

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Frequency</th>
<th>Type</th>
<th>Focal distance</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF 075</td>
<td>75 kHz</td>
<td>planar</td>
<td>30 mm</td>
<td>-34 dB</td>
</tr>
<tr>
<td>CF 200</td>
<td>200 kHz</td>
<td>planar</td>
<td>15 mm</td>
<td>-35 dB</td>
</tr>
<tr>
<td>CF 400</td>
<td>400 kHz</td>
<td>focused</td>
<td>50 mm</td>
<td>-31 dB</td>
</tr>
<tr>
<td>CF 400 3E</td>
<td>400 kHz</td>
<td>Phased-Array</td>
<td>20 mm</td>
<td>-31 dB</td>
</tr>
</tbody>
</table>

3- Examination of thick multi-layer-bonding in through transmission

3-1 Testing of adhesive bonding in transmission

Figure 1 displays the test specimen and the sizing of the artificial flaws. It consists of two 8 mm thick PMMA panels, which are adhesively bonded to each other. In one of the two plates, a test pattern is milled representing artificial defects. This consists of a SONOTEC logo, a SONOTEC logo, three horizontal lines of different thickness and five flat bottom holes with varying diameters. While gluing the two panels, care has been taken that no adhesive enters these recesses. Thus, it can be assumed that they behave like air bubbles inclusions in a flat bond.

A transmission setup was utilized, in which the air-coupled ultrasonic transducers were positioned on both sides of the sample with the active surfaces opposing each other. The distance to the sample surface is adjusted according to the transducer specification in a way that the focal point of the sound beam is formed on the surface. The spatial resolution of the scan was configured as 1 x 1 mm.

The results of the measurement shown in Fig. 2 confirm the good testability of adhesive bonding of plastics. Air inclusions have a significant effect on the amplitude of the measurement signal. With different probes, however, there are differences in the measurement characteristics. Higher frequency can achieve better lateral resolution and differentiate errors that are close together. Nevertheless, even the smallest error can be detected at 200 kHz test frequency. However, due to interference effects beyond a certain wavelength-dependent diameter, these errors no longer show up as attenuation but as an increase in the sound amplitude. Due to the frequency dependent sound attenuation, more amplification may be necessary at higher frequencies. Therefore, a test with a lower frequency even with poorer spatial resolution may be beneficial.

Figure 2: C-Scan of adhesively bonded PMMA plates with artificial flaws with planar 200 kHz probes (l.), mechanical focused 400 kHz probes (m.) and electronically focused 400 kHz phased-array probes (r.)

The comparison between the 400 kHz measurement with mechanically focused transducers (m.) and the measurement with electronically focused phased array transducers (r.) reveals the advantages of electronic focusing. The edges can be resolved more clearly and the flaws are displayed more evenly. In addition, it can be seen that the resolution of the smallest flat bottom hole has been improved. The signal losses measured in the adhesive surface, in particular over the SONOTEC C, are unintentional errors in the surface bonding.
3-2 Testing of sandwich structures with honeycomb core in transmission

Multi-layer composites with honeycomb cores are increasingly used in modern lightweight construction. In particular, the developments in thermoplastic honeycomb cores and cover layers, so-called. Organic sheets open up new applications. The challenge in the production of a sandwich composite with a honeycomb core is the adhesion of the cover layer to the thin honeycomb structure. On the other hand, it must be avoided that the cavities in the honeycomb are filled with matrix material in order to achieve the best possible degree of lightweight construction.

Figure 3: Testing of sandwich structures with 8 mm (l.) and 20 mm (r.) core thickness with the 400 kHz Phased-Array Probe as sending transducer

For this contribution, the examined specimens shown in Fig. 3 are polypropylene honeycomb cores of different thickness with organic sheet top layers from ThermHex. The aim of the investigation, each with two different frequencies, was to analyze the influence of the selected transducers and test frequency on the detectability of individual honeycomb structures, delamination and impact damage.

Figure 4: test result of an 8 mm thermoplastic honeycomb core with a GFRP top-layer with impact damage
left: C & D-Scan with 200 kHz right: C & D-Scan with 400 kHz

Fig. 4 shows the results of the transmission measurement of the 8 mm thick sandwich composite in each case as a color-coded evaluation of the maximum amplitude (C-scan) and the transit time difference of the maximum amplitude (D-scan) for a 200 kHz and a 400 kHz measurement. Due to the frequency-dependent behavior of ultrasound, different results can be obtained from the individual measurements. The low frequency 200 kHz burst is attenuated significantly less by the core and penetrates the plate at all intact locations. The location of the impact damage is characterized by an amplitude collapse. However, the honeycomb structure is only partially resolved by evenly distributed, round amplitude drops. With the 400 kHz measurement, it becomes clear that at this frequency, the webs of the honeycomb transport the sound through the sandwich structure. This is the reason why the signal can only be detected at the locations of the webs. This is also evident in the D-scan, in which the hexagonal honeycomb structure is clearly visible. Since delamination only influences the amplitude, not the transit time, they are not reliably detected in the D-scans. However, if the amplitude of the measurement burst collapses completely, this location may become visible as an artifact displaying the noise. This can be observed in the 200 kHz D-Scan at the location of the impact.
A similar result emerges in the case of the evaluation of the measurements on the 20 mm sandwich panel depicted in FIG. 5. It can be observed that the longer transit distance in the thicker honeycomb increases the attenuation of the 400 kHz signal significantly deteriorating the SNR. Nonetheless, the delamination can be identified at both frequencies, due to the high dynamics of the modern test system. The complete collapse of the signal amplitude at the delamination is reflected as noise in the D-scan. In the 400 kHz measurement, this is also the case for the honeycomb spaces.

3-2 Testing of thick SMC-Composites in transmission

In the manufacturing process of insulation boards made of SMC composite material, process-induced fluctuations can result to air bubble formation in between the glass fiber mats. In certain applications, these air bubbles can adversely affect the desired properties of the plates. The air-coupled ultrasonic technology provides a non-destructive testing possibility for the large semi-finished slabs after the pressing process to identify areas with air bubbles. decidated probes were selected which are able transmit sufficient sound intensity through the material. The reduced spatial resolution due to the low frequency was counteracted with a specially developed post-processing algorithm, comparing the scan result to a reference sample. Additionally, this will reduce the effect of the interference patterns at the edges of the specimen. The result of this process is illustrated in Fig. 7 with an example.
The method thus developed allows for testing of semi-finished products with a subsequent good (i.O.) / bad (n.i.O.) Rating. The simple green-blue-red display can be used for automated detection of i.O. areas to evaluate which zones can be used for further production steps.

3-3 Single-sided Examination of adhesive bonding using guided waves

3-4 Detection of flaws in adhesive bonding of CFRP-aluminum-compounds

In the evaluation of flaws in hybrid bonds it is of interest which interface is faulty. As can be seen in Fig. 8, the areas of incomplete adhesion can be determined by means of transmission measurement. These bonds would thus be referred to as i.O. rated. For an improvement of the bonding process, however, the knowledge of the side of the faulty bonding is also desired. This information can be obtained by an additional test with guided waves.

The guided wave generation and detection method used for the test was described and explained by Kiel et al. in [4] in detail by means of the examination of welds. For this reason, this article does not deal in depth with the derivation of the converter angles and the necessary positioning distances.

The comparison of the measurement on the CFRP side in the left image and the aluminum side in the right image of Fig. 9 with the results from the transmission measurement reveals that the adhesive has bonded with the fiber composite plate and the adhesive defect lies at the boundary layer to the aluminum.
Figure 9: single-sided measurement using guided waves – CFRP - side (l.) and aluminum- side (r.)

In the interpretation of the C-scans of guided waves it is necessary to consider that the transducer distance of the measuring arrangement leads to a distortion of the scan in one scanning direction. For this reason, the bonded areas known from Fig. 8 are shown elongated and distorted in Fig. 9.

3.5 Guided waves in complex parts - pipe with glued-in core

The characteristics of guided waves enable tests on complex component geometries where sound transmission is not practical. This is to be demonstrated on a wound GFRP pipe with glued-in core made of GFRP laminate. The goal is to prove the homogeneity of the adhesive layer. Incorrect bonding can lead to the formation of air pockets, which may lead to unwanted ingress of water due to capillary action. This in turn could lead to a failure of the component in case of frost.

Fig. 10 showcases the principle of eccentric testing of tubes using guided waves, which is described in [5] by Takahashi et al. A transmission setup is utilized with 400 kHz phased array transmitters and receivers facing each other. This setup exploits a slight offset from the cross-sectional central axis of the pipe, whereby the frequency-dependent insonification angle $\phi_t$ is set at a distance $\Delta D(r)$ and a guided wave in the cladding material is excited. In Fig. 11, the measurement principle can be seen in the scans of two tubes, in which a maximum of intensity is established on both sides of the center of the tube at the same distance from the center.

In the special case, in which the FKV layers of the core are parallel to the incident angle, in addition to the circulating guided waves, there is still an intensity maximum in the center of the pipe. This is created by ultrasound, which propagating along the fiber layers. However, once the tube is rotated, each individual layer acts as an inclined boundary layer. For this reason, transmission measurement is generally impractical due to the high attenuation at 400 kHz through the center of the tube.
When evaluating the scans, interference pattern can be observed in the incompletely bonded tube. These lead to an uneven intensity distribution in the received signal. Furthermore, the reception maxima are farther from the center of the tube at 0, suggesting a slower wave.

![Image](image.png)

Figure 11: Testing the adhesion of a pipe to a glued-in core

- top: incomplete attachment
- below: complete attachment

For a slower wave, the maximum in the signal amplitude occurs at a larger distance between the transducer and the center of the tube. This means that in this case the excitation angle $\phi_t$ on the pipe surface is larger (excitation angle $\phi_t$ is the angle to the normal, in the center of the pipe it is 0°, at the distance $r$ = pipe radius the excitation angle is equal to 90° - grazing incidence). The larger the excitation angle becomes, the smaller is the wavelength of the excited guided wave in the plate (formula (1) in [11]) and hence its propagation speed. In Fig. 11, the distance between the maxima in the measurement of incomplete bonding in the upper image is bigger than in the measurement of the complete bond in the lower image. Assuming that the thickness of the wave-guiding layer is thinner in the case of delamination, this can be taken as an indication that the excited measuring signal is an a0-mode lamb wave (see dispersion diagram).

4- Conclusion

Using various ACUT examples, a spectrum of solvable test tasks could be presented. Depending on the task, the test setup utilized through transmission or guided waves. Very high attenuation materials were tested by reducing the spatial resolution at lower frequencies. The basis for successful application of ACUT is the multichannel capability, the highly sensitive ultrasonic transducers and the high amplifier dynamics of current test systems.

5- Acknowledgment

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References

2. Oster, R.: “Non-destructive testing methodologies on helicopter fiber composite components challenges today and in the future” - 18th World Conference on Nondestructive Testing, 16-20 April 2012, Durban, South Africa