NON-CONTACT ULTRASONIC IMAGING TECHNIQUES FOR COMPOSITE COMPONENTS

W. Hillger[1], M. Ahrholdt[2], H. Rohling[2], R. Henrich[3]
[1] DLR (German Aerospace Center), Braunschweig, Germany; [2] Technische Universität Hamburg-Harburg, Germany; [3] Airbus, Bremen

Abstract: This paper presents non-contact ultrasonic imaging techniques with air coupling. The work is conducted as a part of the German research project MaTech. Project partners are Airbus, Bremen, IntelligeNDT, Erlangen, Ingenieurbüro Dr. Hillger, Braunschweig, the Technical University of Hamburg-Harburg and DLR, Braunschweig, as a subcontractor. A modular and open ultrasonic imaging system (demonstrator III) which provides the capability for basic research of air coupled ultrasonic techniques for composites has been developed. Highlights are: a freely programmable transmitter, fast full-wave data recordings (12 bit) and software C- and D-scans. Especially promising testing results can be achieved by the application of suitable transmitter signals and processing of the received signal. In this paper, both frequency-modulated and coded signals are considered for transducer excitation. This works particularly well for broadband air coupled transducers, for which the signal is chosen adaptively. For the received signal, a matched filter processing is applied depending on the transmitter signal. Measurement results show a significant improvement of the signal-to-noise ratio especially for thicker components.

Introduction: The increase of composite materials for aircraft applications requires a growing need for NDT. The aircraft industry is using more and more thick CFRP- and CFRP-sandwich components with honeycomb and foam core. Those materials are highly attenuative. Sandwich materials can only be penetrated with frequencies in a range of about 50 to 500 kHz.
The airborne ultrasonic technique avoids the disadvantages of the common ultrasonic technique with coupling liquid or coupling paste like time-consuming cleaning, incoming water, air bubbles in immersion technique, etc. [1-4]. On the other hand, the acoustic impedance mismatch between solids and gas (air) produces an amplitude loss of more than 150 dB using a standard ultrasonic equipment. Therefore special transducers with an impedance matching to air, a powerful excitation of the sender and a matched ultra-low preamplifier are required.

Results: *Ultrasonic system.* The developed air coupled ultrasonic imaging system USPC 4000 AirTech (Fig. 1) is a further development of the “demonstrator 3” [5] of the MaTech project. This system provides high pulse repetition frequencies in order to get high scanning speeds. The hardware built in an industrial PC with Windows operating system consists of programmable high power pulser with a digital arbitrary generator, an ultra low noise preamplifier, a main amplifier and a ADC-board with a resolution of 12 bits. All measuring functions such as amplitude (gated peakdetector) and time-of-flight measurements are carried out by software. The system does not only provide C-scanning but also full-wave scans with software A-, B-, C-, D- scans. Additional functions are echo-technique (in order to measure the distances between the transducers and the specimen) and the application of chirp and coded signals. The software also enables digital filters for the enhancement oft results. The system is working with transducers from different manufactures.

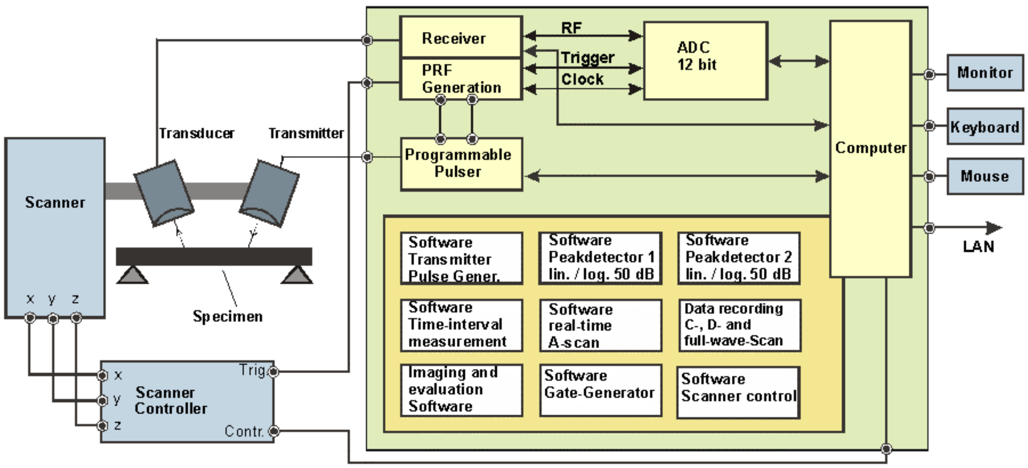


Fig.1: Block diagram of USPC 4000 AirTech

Transducers

Several transducers from different manufactures have been evaluated for ultrasonic imaging. The most interesting parameters are sensitivity, centre frequency, bandwidth, focus point and beam diameter. Most of them are resonant transducers with a small bandwidth in order to get a high efficiency. A few of them showed side lobes in their sound fields. For optimising the distances between transducers and specimen, it is useful to record the sound field with a ball reflector.

In order to get a high power broadband pulse, a stack transducer [6] (Fig. 2) has been investigated. This kind of transducer consists of eight elements, which are acoustically coupled and electrically insulated. At the back wall of the piezo-element 1, an acoustic damping is situated, at the front (sound output, element 8), an impedance matching to air is situated. All elements are excited with delayed pulses S_1 to S_8. The delay times t_2 to t_8 are adjusted in the way that the passing pulse from element 1 through element 2 to 8 is amplified by the pulses S_2 to S_8. In the ideal case, the output of the element 8 provides an 8-fold higher pulse compared with a standard transducer.

This technique can also be applied on the receiver side. The receiver stack transducer built in the same way, delivers 8 delayed pulses which have to be added with the right phases. Theoretically, a gain of 18 dB can be reached in comparison with a single element transducer on the receiver and on the transmitter side. For this kind of stack transducer, an ultrasonic system with eight channels has been developed. But the results show some disadvantages: The acoustic coupling between eight elements cause a „ringing“ so that no single highly damped pulse has been generated. Therefore, the echo-technique could not be used. Also the impedance matching to air was not very successful, so that the sensitivity s, defined by:

$$s = 20\log\frac{V_R}{V_T} \qquad (1)$$

(V_T = excitation in Volts, V_R= receiver signal amplitude in Volts),
reaches only -49 dB.

Tab. 1 compares the data of the stack transducers with commercially available transducers. The bandwidth of the stack transducer is the largest one. The sensitivity of -49 dB is very low in comparison with the transducers 1 and 2 (-38 and -41 dB). Investigations show that the sensitivity should be >-40 dB for aircraft materials like CFRP-Sandwich and CFRP-laminates if only bust excitation and a single-shot receiver technique are used. The high bandwidth of transducer 3 permits the application of chirp and coded signals (see below).

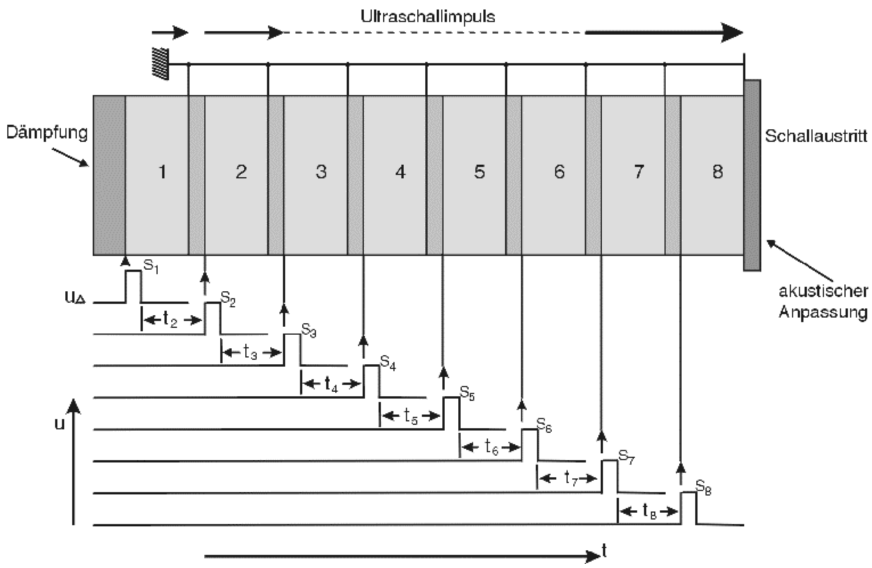


Fig. 2: Eight element stack-transducer

	8-element stack transducer	**Transducer 1 (single element)**	**Transducer 2 (single element)**	**Transducer 3 (single element)**
Active diameter [mm]	21	19	25	19
Max. frequency [kHz]	313	122	189	632
Frequency range [kHz]	272-362	11-136	157-217	569-729
Rel. bandwidth [%]	31	14	32	23
Impedance [Ω]	300	1,43 k	916	238
Optimal excitation	T=1.4µs, n=1	T= 4,020 µs, n=7	T=2.76µs, n=4	T=0.62µs, n=1
Sensitivity [dB]	-49	-38	- 41	-73
Beam diameter [mm]	6	13	9	5.5

Tab: 1 Parameters of 8-elements stack transducer and selected single element transducers

Inspection of sandwich components A sandwich test specimen (Fig. 3) with CFRP-skins (each with 1.25 mm thickness) and two different foam core materials (different densities) was used for the examination with burst excitation. The component with dimensions of 487 x 171 mm and a total thickness of 35,7 mm contains several artificially inserted flaws: on the left hand side two debondings (with a width of 10 mm) between the upper and the lower skin), three bore holes (8 mm in diameter) and on the right hand side a bore hole of 10 mm in diameter. Due to the high attenuation of this component, a pair of transducers 2 with a nominal frequency of 200 kHz was used for the tests in through-transmission technique. For the excitation, a burst of 5 cycles with a centre frequency of 166 kHz has been applied.

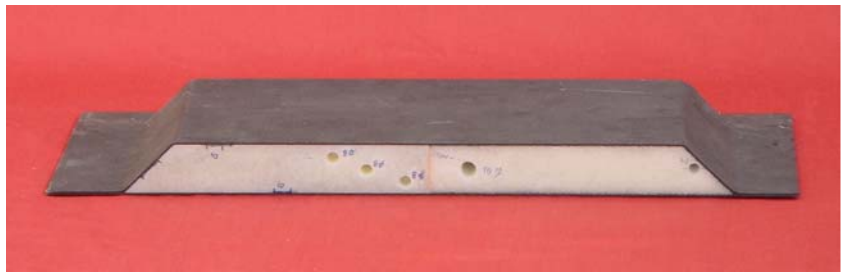


Fig. 3: CFK-sandwich specimen with artificially inserted defects

Fig. 4 shows the A-scan with a gate for amplitude measurements and the frequency spectrum. The pulse width is relatively short (35 µs) because of the frequency range from 158 to 190 kHz.
The component has been scanned with a speed of 300 mm/s with a grid of 2 mm, so that a pulse repetition frequency of 150 Hz was reached.
The C-scan (in through-transmission technique) (Fig. 5) gives a clear indication of all defects. Because of the two different foam cores the left part is plotted in blue (amplitude of -3dB) and the right part in yellow (-17 dB). The delaminations of the upper and of the lower skin decrease the amplitude of -15 dB, the bore holes cause -4 dB.

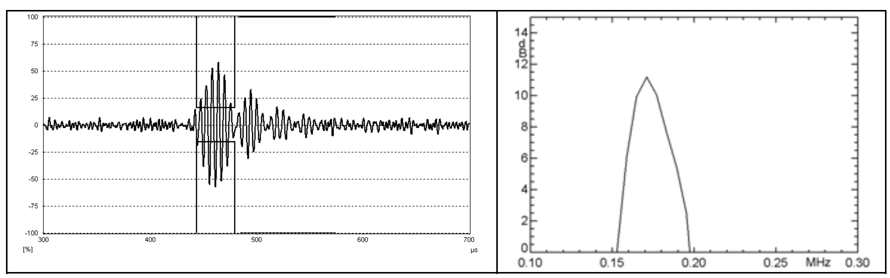
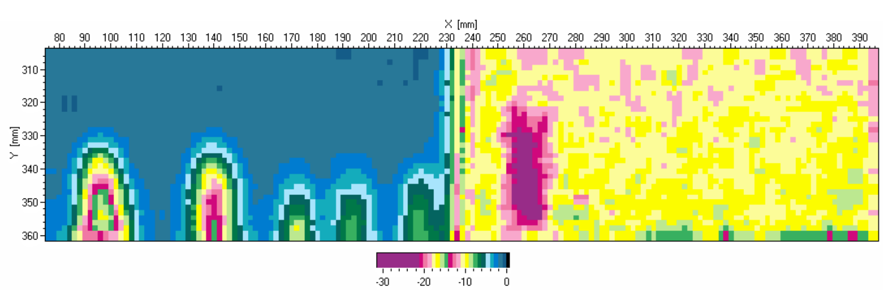


Fig. 4: A-scan and frequency spectrum (158-190 kHz) of a sandwich with foam core

Application of Coded and Chirp Signals

The system performance can be further improved by employing a suitable coded or frequency-modulated transmitter signal and a processing of the received ultrasonic signal (Fig.6). In particular, testing limitations can be overcome for situations with high attenuation and low ultrasonic received signal amplitudes, e.g. for the examination of thicker laminates.
The concept of pulse compression allows to transmit a specially designed signal over a certain time duration and thus to increase the total signal energy. Then, a receiver filter is used to concentrate the energy and to compress the signal duration.



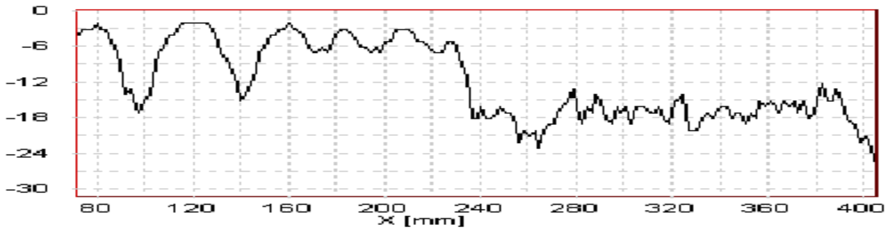


Fig. 5: C-scan and amplitude-dynamics of a CFRP-sandwich component with foam core

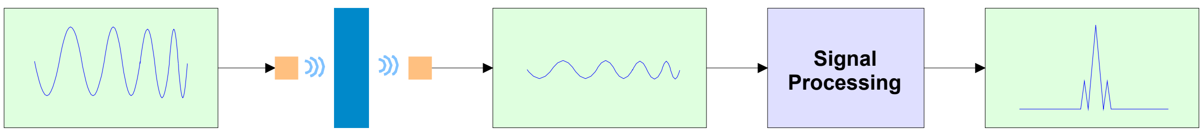


Fig. 6: Pulse Compression

The transmitter signals are chosen adaptively according to the transducers' specification. Either a frequency-modulated signal (called chirp) or a coded transmitter signal is applied, see Fig. 7. For a chirp signal, the modulation bandwidth is adapted to the transducer bandwidth. For this reason, a broadband transducer gives better compression properties.

The matched receiver filter can be derived from the transmitter signal. Its purpose is to allow the detection of the transmitter signal in a noisy environment. The common approach [7] is to consider the filtering as a correlation process which utilises the similarity of transmitted sequence and received signal.

The frequency-modulated chirp transmitter signal is computed as

$$s(t) = \cos(2\pi \ f_M(t)\, t) \tag{2}$$

with a varying current frequency $f_M(t)$. The advantage of modulated signals is that they can easily be adjusted to the bandwidth available for transmission.

Another approach for pulse compression uses coded signals [8-10]. The transmitter signal is defined as

$$s(t) = c(t)\cos(2\pi \ f_0 t) \tag{3}$$

with the current code symbol $c(t)$ and the centre frequency f_0. In this case, the utilized spectrum depends both on the signal duration and the applied code. It can be adapted by adjusting these parameters to fit the available transmission bandwidth. For coded signals, the matched filtering can either be applied directly on the received signal, or on a demodulated signal yielding a better computational performance.

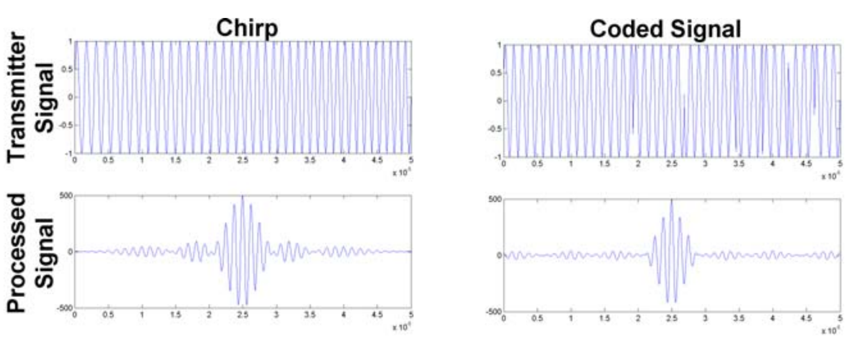
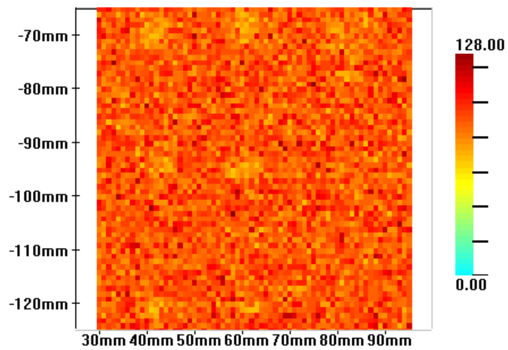


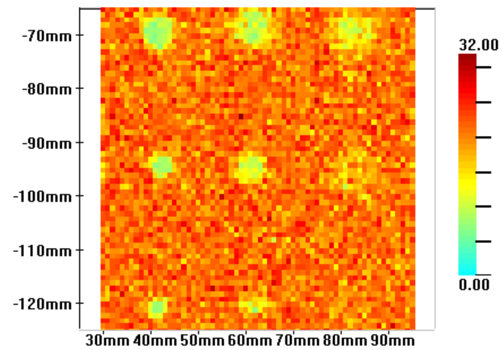
Fig. 7: Chirp and Coded Signal

Results on Coded and Chirp Signals

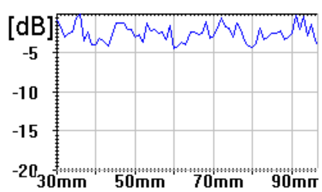
The described transmitter signals and processing algorithms have been applied on several measurements in a real environment with air-coupled through-transmission testing of carbon-fibre reinforced plastics (CFRP) components using transducer 3 (Tab.1). The examination of a CFRP sample of 9 mm thickness is depicted in Fig. 8. In this case, a particularly low transmitter amplitude is used to demonstrate the processing capabilities. It shows in Fig. 8 (a) the C-scan of an unprocessed signal of 50 µs duration. Fig. 8 (b) gives the C-scan of the processed coded signal. The delaminations inside the material are visible only in the processed signal's image. Fig. 8 (c) and (d) compare the respective amplitude dynamics (for *y*= -69 mm). While the unprocessed signal does not show any contrast between flaw-free and delaminated areas in the raw signal, the processed signal gives approx. 8 dB contrast between the considered areas.



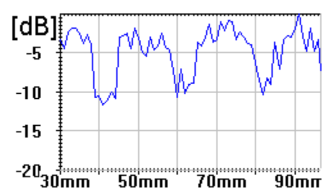
(a): C-Scan before Processing



(b): C-Scan after Processing



(c): Amplitude Dynamics before Processing



(d): Amplitude Dynamics after Processing

Fig. 8: C-Scans and Amplitude Dynamics of 9 mm CFRP Sample

Another example is the testing of a step wedge with thickness of 10, 20, 30, 40, and 50 mm given in Fig. 9. Here, the B scans of the processed signal show the detected signal peak in contrast to the surrounding noise. In Fig. 9, the detection results with standard burst excitation are compared to the results for coded and chirp transmitter signals. With conventional burst excitation, the detection of the ultrasound pulse becomes impossible from 20 mm thickness of CFRP material. With a chirp transmitter signal and matched processing, detection is still possible with a certain probability at a thickness of 50 mm. Fig. 10 gives the detection probabilities at the considered material thicknesses. These figures allow a comparison between the different transmitter signals, clearly indicating that the best performance is achieved for the chirp signal in this experiment.

Thickness	**Conventional Burst Excitation**	**Coded Transmitter Signal and Matched Processing**	**Chirp Transmitter Signal and Matched Processing**

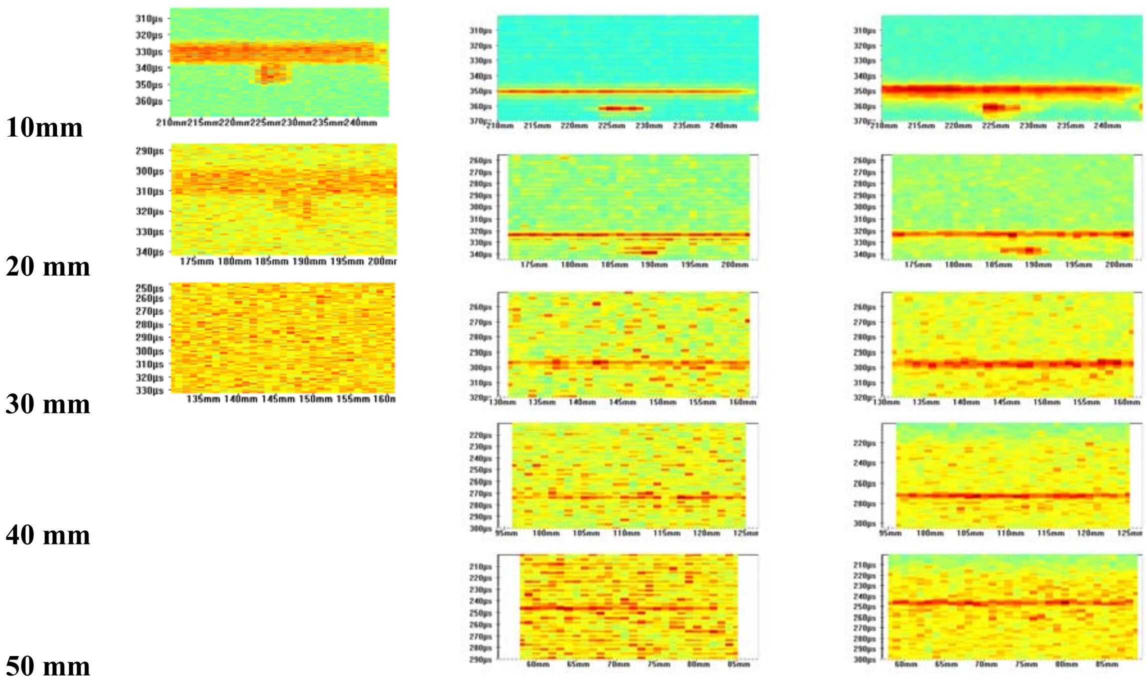


Fig. 9: Results of Pulse Compression at Step Wedge

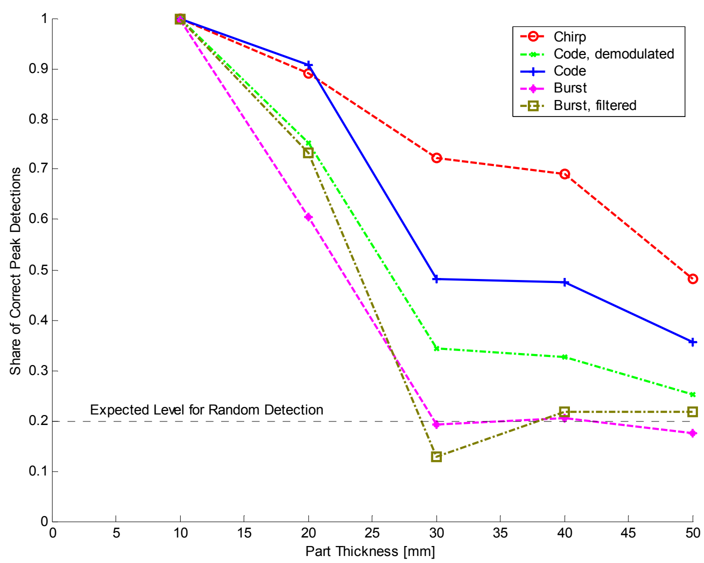


Fig. 10: Probability of Detection Depending on Material Thickness

Discussion: The airborne ultrasonic technique enables non-contact imaging of defects and a quality control of CFRP laminates and sandwich parts for aircraft components without coupling problems. For these applications, the ultrasonic system USPC 4000 AirTech has been developed, different excitations such as tone burst-, chirp and coded signals have been examineded. Also transducers from different manufactures have been evaluated. In order to get a high sensitivity, most of the transducers are nearly undamped and produce long pulses. However, for a high PFR, short pulses are required. Principally, stack transducers consisting in our case of eight elements, provide high power broadband pulses. A prototype delivered a high bandwidth but a too small sensitivity. In dependence of the transducer bandwidth, different cycles of tone burst are used for the excitation. The application of coded and especially chirp signals for the excitation and matched filters on the receiver side increase the signal-to-noise ratio to 8 dB and more.

Conclusions: The key technologies for airborne ultrasonic technique are the ultrasonic system and the transducers. During the described investigations, a new generation of transducers have been developed which provide a high sensitivity and high bandwidth [11]. Using these kind of transducers with a few cycles of tone burst for the excitation, the USPC 4000 AirTech delivers best results fast imaging. Excitations with chirp or coded signals produce advantages especially with long transmitter pulses which decrease the PFR and thus increase the time for scanning. Therefore these techniques are only useful if the signal-to-noise ratio is too low for burst excitation.

References: [1] Grandia, W.A.; Fortunko, S.M.:NDE Appplications of Air-Coupled Ultrasonic Transducers, 1995 IEEE International Ultrasonic Symposium Seattle, Washington, Conf. Proc.,1995, S. 697-709.
[2] Hillger, W.: Ultrasonic Testing of Composites - From laboratory Research to In-field Inspections, 15th World Conference on Nondestructive Testing, Roma (Italy) 15-21
[3] Gebhardt, W.; Hillger, W.; Kreier, P.: Airborne Ultrasonic Probes: Design, Fabrication, Application, 7. ECNDT, Kopenhagen, 26-29 Mai, 1998
[4] Bhardwaj, M. C. : High transduction piezoelectric transducers and introduction of Non-Contact analysis, www.ndt.net/article/v05n01/bhardwaj/bhardwaj.htm
[5] Hillger, W.; Meier, R.; Henrich R.: Inspection of CFRP Components by Ultrasonic Imaging with Air Coupling, Insight, Vol 46, No3, March 2004, pp 147-150.
[6] Gebhardt, W.: Einsatz von luftgekoppelten Ultraschall-Leistungswandlern in der ZfP, DGZfP-Jahrestagung 1999, Celle, 10.-12. Mai 1999, Berichtsband 68, Band 1, pp. 55-62.
[7] Lüke, H.-D.: Korrelationssignale. Springer-Verlag, Berlin, 1992.
[8] Barker, R. H.: Group Synchronizing of binary digital Systems. In *Symposium on Applications of Communication Theory*, London, 1953
[9] Plagge, W.: Pulskomprimierende Verfahren zur simultanen Echolaufzeit und Dopplerfrequenzmessung in der Ortungstechnik. Dissertation, Technische Universität Braunschweig, 1995.
[10] Rohling, H.; Borchert, W.: Zum Mismatched-Filter-Entwurf für periodische binärphasencodierte Signale. ntz Archiv, 10(5):, pp. 111-117, 1988.
[11] Bhardhwaj, M. C.: High efficiency non-contact transducers and very high coupling piezoelectric composite, 16th World Conference on Non-Destructive Testing, Montréal, Canada, August, 30. to Sep. 03. 2004, Conf. Proc. in preparation .