



# Focusing Air-Coupled Ultrasonic Transducers Based on Ferroelectrets

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**Abstract.** Rising importance of composite lightweight structures in aircraft and automobile industries increases the demand on reliable non-destructive testing methods for these structures. Air-coupled ultrasonic testing emerged to suit these requirements as it does not require any liquid coupling medium. In conventional air-coupled ultrasonic transducers, matching layers are used in order to decrease the impedance mismatch between transducer and air. Matching layers can be omitted by using ferroelectrets, which are charged cellular polymers having ferroelectric and piezoelectric properties. Especially a low Young's modulus, low density and low sound velocity of cellular polypropylene (cPP) are properties being required for well-matched air-coupled ultrasonic transducers.

In our contribution we show recent enhancements of cPP transducers resulting in focused sound fields and thus improved lateral sensitivity. The influence of different transmitter apertures was evaluated using measurements of the emitted sound field. Further we show a transmission of a test specimen of carbon-fiber-reinforced plastic (CFRP) containing artificial damages. Results of focused transducers were compared to planar ferroelectret transducers, as well as to conventional air-coupled transducers.

## 1. Air-Coupled Ultrasonic Inspection of Lightweight Structures using Ferroelectret Transducers

The increasing need to save fossil fuels and reduce fuel consumption raises the importance of lightweight materials in modern industrial production. In aerospace industry fuel consumption is directly connected to material weight, but also strict fuel economy standards are forcing the automobile industry to use more lightweight structures. Traditional materials are replaced by lightweight and high performance composites like carbon-fibre-reinforced plastics (CFRP). The latter accounts a significant huge percentage of the total weight of a modern commercial airplane. Complex shapes and sensitive core material of composite structures are a challenge for non-destructive testing (NDT). Air-coupled ultrasonic testing (ACUT) emerged as a promising alternative to conventional contact technique [1]. Constant coupling and easy maintenance are advantages of ACUT, as well as the fact that no coupling medium as water or oil is required. In contrast to contact technique, the large impedance mismatch between transducer and air is challenging the manufacturers of air-coupled transducers. Matching layers used on commercial air-coupled transducers based on piezo



ceramics in order to reduce this impedance mismatch represent a compromise as they have a negative impact on transducers properties.

Most promising alternative to transducers based on piezo ceramics are ferroelectrets, which are charged cellular polymers having ferroelectric and piezoelectric properties. With a thickness of 70-90  $\mu\text{m}$ , a density of 330  $\text{kg/m}^3$  and a longitudinal sound velocity of 80  $\text{m/s}$  films of cellular polypropylene (cPP) have shown to have good properties to suit most requirements for air-coupled transducers [2-4]. The resulting impedance of only 0.03  $\text{MRayl}$  allows omitting any matching layers, which are required with commercial air-coupled transducers [5]. cPP transmitters can be excited with high voltage pulses up to 2 kV in order to generate the required sound pressure for ACUT. When excited with this high voltage, there exists a significant electrostatic compression additional to the piezoelectric effect due to a low elastic modulus of the cPP film. Ultra-low noise pre-amplifiers of the receiving transducers have an extremely high input impedance of 100  $\text{M}\Omega$  at 10 pF to match the output impedance of the receiving transducer, which is between 1 and 10  $\text{M}\Omega$ , depending on the transducer aperture.

In this contribution we present sound fields of focused and non-focused cPP transducers, as well as the influence of different apertures. Focal distance and size of prototypes are being measured. Prototypes of cPP transducers are compared to commercially available transducers using a CFRP plate with artificial damages. We show transmission inspection results and compare the signal-to-noise ratio (SNR) of all tested transducers.

## 2. Spherical Focusing of Cellular Polypropylene Transducers

Gluing cPP film on a curved surface without influencing its original electromechanical performance has been demonstrated previously [13]. In order to achieve a focusing effect, a cPP film can be deposited on a spherical surface. The difficulty of depositing a film on any non-developable surface, like a sphere, is stretching and compressing of the film without producing any wrinkles and areas of declined sensitivity due to mechanical stress and strain.

A circuit board containing a circular electrode was used as a substrate for the transducer. This substrate was bent at increased temperature by using a spherical calotte to a curvature radius of 50 mm. This creates the required spherical surface for the cPP film HS06-20-BR. As the influence of different apertures was to be investigated, transducers of 11, 19 and 27 mm aperture were built. Fig. 1 depicts a prototype of an aperture of 19 mm with electrical matching unit.



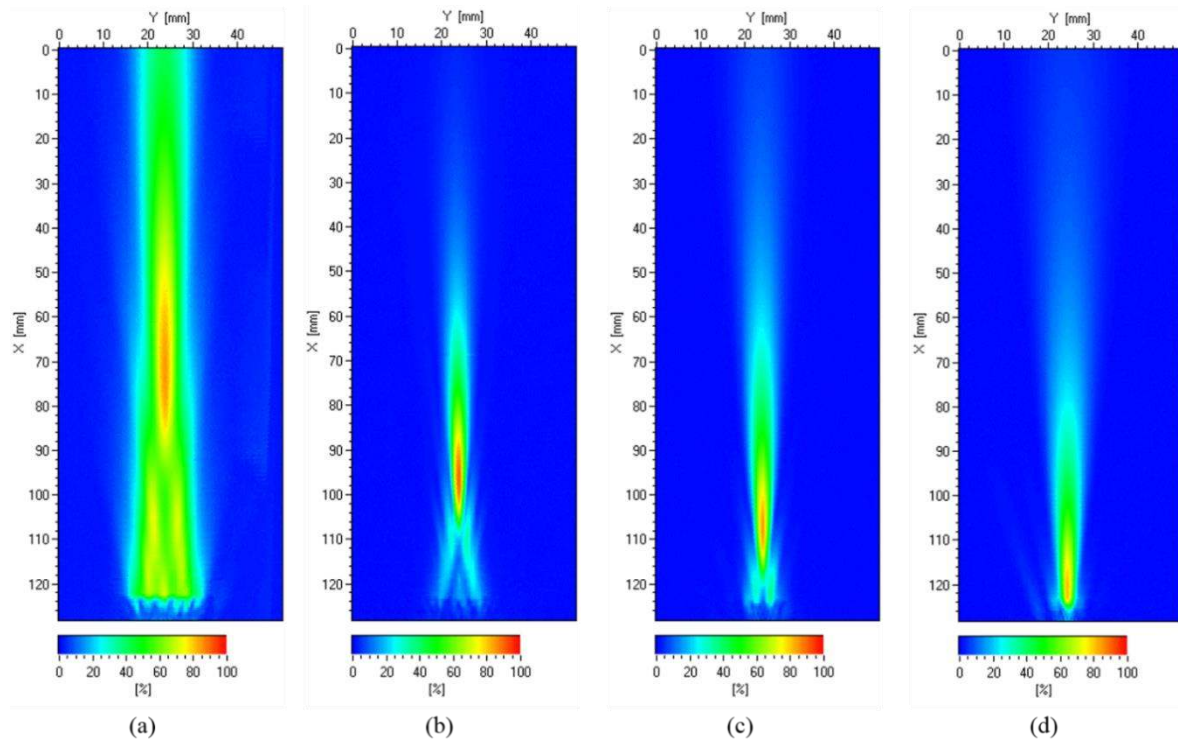
**Fig. 1.** Focusing transducer for air-coupled ultrasonic testing based on cellular polypropylene (front) with electric matching unit (background)

The aperture size is equal to the size of the inner electrode, which may be smaller than the outer one, whereas the inner electrode is placed on the circuit board and the outer

electrode is evaporated on the cPP-film itself. The outer electrode on the cPP film was realised by using electron beam evaporation and is earthed over pressure contact with the transducer's housing. The resonance frequency was determined to be between 250 kHz and 300 kHz depending on the evaporation process details.

### 3. Sound Field Measurements of Focused cPP Transducers

The European standard EN 12668-2 gives a method to measure the sound field of transducers for immersion testing. Equivalent two-dimensional measurements were performed with air-coupled transducers in air instead of water with pulse-echo technique. A bar reflector with 6 mm diameter was used in order to reflect the sound wave. In this setup the tested transducer is used as transmitter and receiver. The transducer was pulsed with a rectangular pulse with a voltage of 1.8kV and a pulse length of 2 $\mu$ s. Measurements were performed with the commercially available ACUT System "USPC 4000". Moving the vertical bar reflector normal to the horizontal plane of the acoustic axis "x" allows recording the reflected echo of each point in the x-y plane. Measurements were performed with focused cPP transducers of an aperture of 11 mm, 19 mm, and 27 mm. A non-focused planar cPP transducer of an aperture of 19 mm was used as reference. The detected echoes were analysed by determining the amplitude of the ultrasound wave resulting in one single value for each point in the x-y plane. Fig. 2 shows the resulting sound field which maps amplitude values in the x-y plane (C-Scan). The transducers are located at  $x_{\text{transducer}} = 145$  mm.

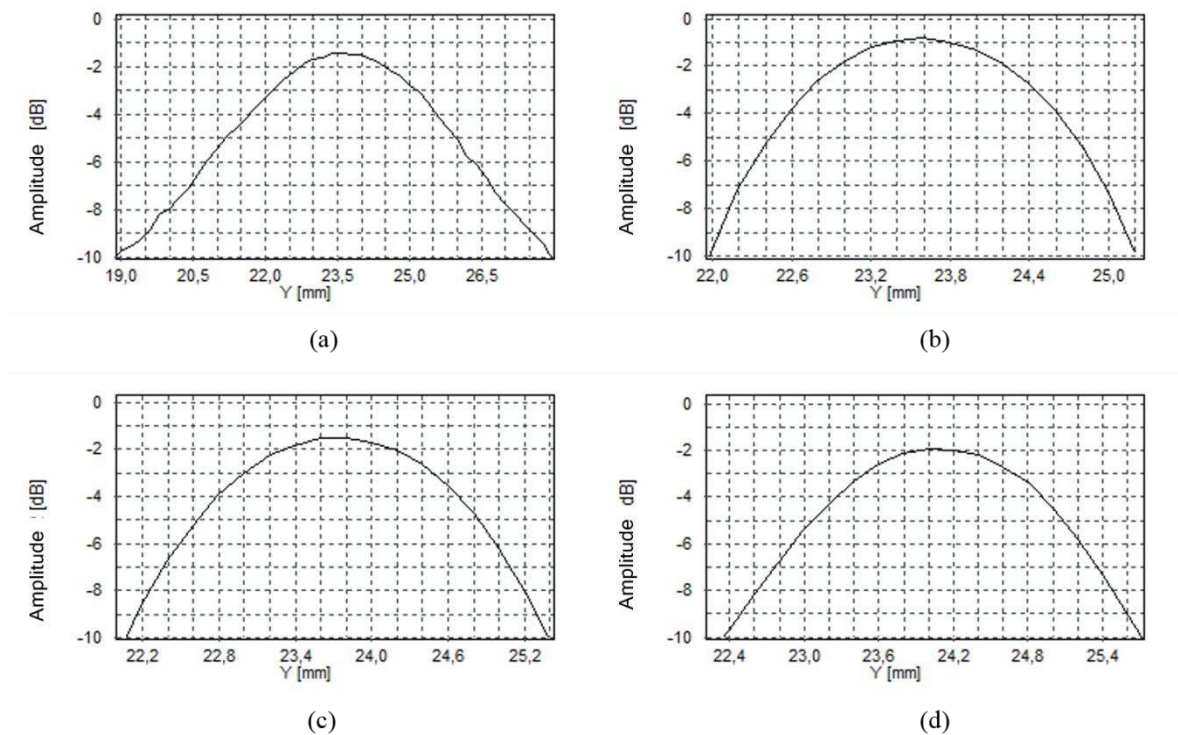


**Fig. 2.** Sound field of cPP transducers: (a) non-focused, aperture 19 mm; (b) focused, aperture 27 mm; (c) focused, aperture 19 mm; (d) focused, aperture 11 mm

It can be seen, that the focal distance of a transducer is strongly influenced by two parameters. One is the aperture due to geometrical interference of discrete waves being emitted from each point on the transducer's surface. The other one is the curvature radius of the transducer's surface which is constant for all tested focused transducers but infinite for

the planar, non-focused reference transducer. Measurements show a significant influence on the focal distance: it decreases from 70 mm to 41 mm for the focused transducer compared with the non-focused transducer of the same aperture of 19 mm. It can also be seen, that the focal distance decreases with the aperture size from 54 mm for an aperture of 27 mm to 24 mm for an aperture of 11 mm. For distances closer than 20 mm to the transducer the measurement does not give any information about the sound field due to the time window limitation.

The focal size was determined by the -6 dB decrease of the sound amplitude at focal distance. Fig. 3 shows cross sections of the sound field. The focal size was measured to be between 2 and 3 mm for all three apertures of focused cPP transducers, whereas the focal size of a non-focused cPP transducer of 19 mm aperture was between 6 and 7 mm. A similar result was obtained by a numerical simulation using point source synthesis, assuming piston-like behaviour and a sine-wave resonance of the transducer.

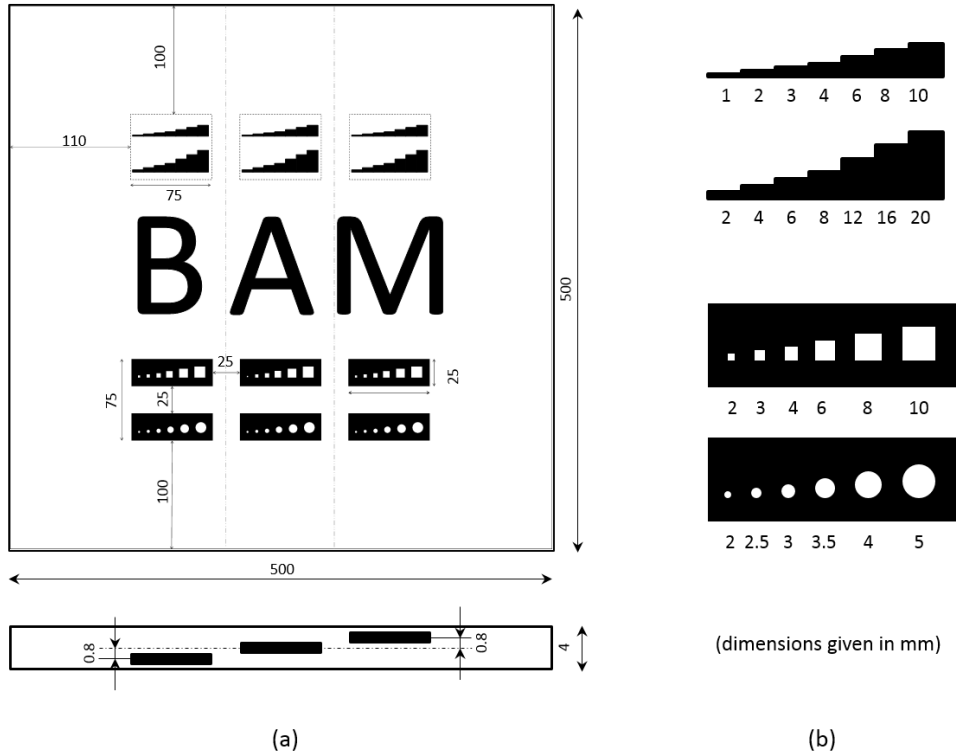


**Fig. 3.** Sections of sound field measurements of air-coupled transducers: (a) non-focused, aperture 19 mm; (b) focused, aperture 27 mm; (c) focused, aperture 19 mm; (d) focused, aperture 11 mm

#### 4. Inspection of CFRP with Focused Air-Coupled cPP Transducers

A transmission of a carbon-fibre-reinforced plastic (CFRP) plate with inserts representing delamination was performed with focused cPP transducers in order to show the influence of the focusing effect shown above. The CFRP plate consists of a carbon fibre plain weave Tenax Style 427 with 0°/90° fibre direction and epoxy resin as matrix system. 10 layers of carbon fibre were used to build up a thickness of 4mm. Inserts representing delamination were placed on top of layer 3, 5 and 7 (Fig. 4). The material used for inserts is the same cPP film which is used in the transducer as its acoustic impedance of only 0.03 MRayl is sufficiently far from the impedance of CFRP, which is about 4.5 MRayl. This way ultrasonic wave reflection at a cPP insert will be about the same as from delamination, representing thin air gaps.

In order to maximize lateral resolution, the CFRP test piece was placed at focal distance between transmitter and receiver unit. Three different sets of transducers were used: focused cPP transducers, non-focused cPP transducers and commercially available focused transducers. The excitation voltage was 1.8 kV for cPP transducers and 400 V for commercial ACUT transducers, as recommended by manufacturer. The pulse length was set to half period of each transducer's resonance frequency in order to maximize the transmitted sound amplitude.

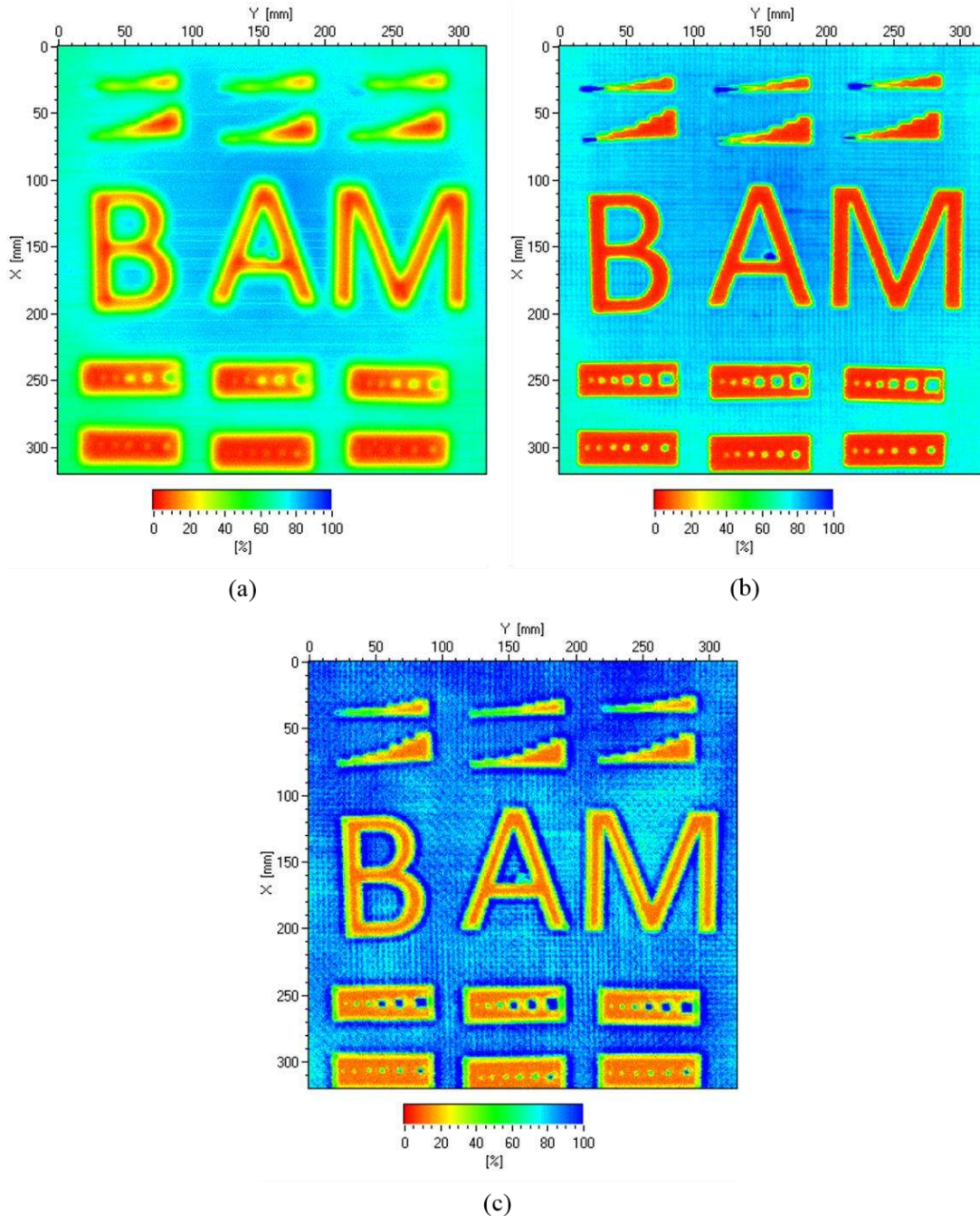


**Fig. 4.** Test piece: CFRP plate with delamination inserts: (a) positions and (b) dimensions of inserts.

## 5. Inspection Results

Fig. 5 shows transmission inspection of the CFRP plate with inserts. Focusing cPP transducers are compared to non-focusing cPP transducers and commercially available focusing air-coupled transducers. The commercially available focusing air-coupled transducer NCG500-D19-P50 from company Ultrason has a resonance frequency of 330 kHz (although nominally 500 kHz) and a focal length of 37 mm. All three sets of transducers have the same aperture of 19 mm.

Focussing of cPP transducers results in a significant increase of lateral resolution. In spite of the smaller resonance frequency of 250 kHz, the focussing cPP transducer produced an image with a slightly better lateral resolution than the commercially available one. Presumably this is because of a smaller focal size.

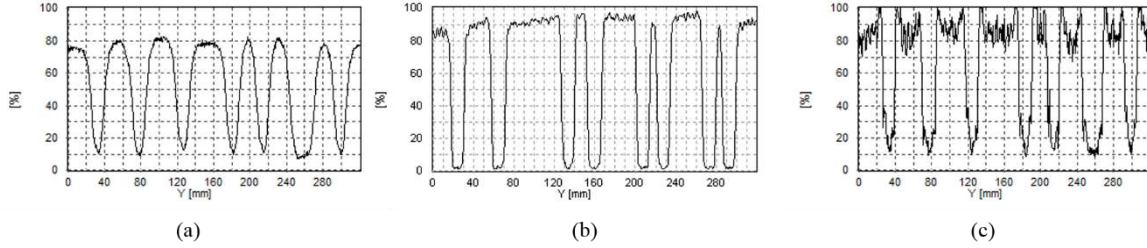


**Fig. 5.** Transmission inspection of CFRP test piece with delamination inserts using (a) non-focusing cPP transducer at 270 kHz, (b) spherically focusing cPP transducer at 250 kHz and (c) NCG500-D19-P50 at 330 kHz

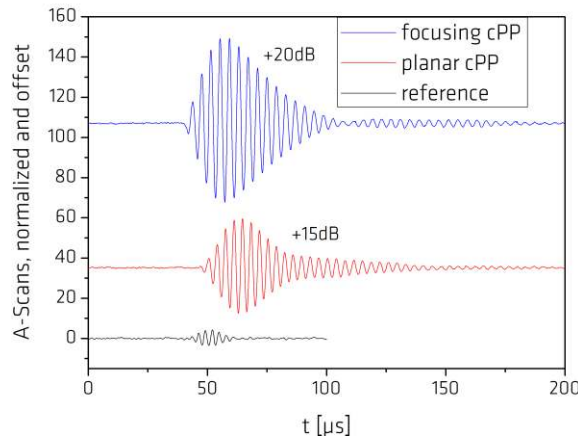
Cross sections of transmission inspection were created as depicted in Fig. 6 in order to show the contrast of each transducer. Both, the non-focused cPP transducer and the commercially available transducer NCG500-D19-P50, produce a contrast of 18dB. The focused cPP transducer produces a significantly higher contrast of 33dB.

Fig. 7 shows A-Scans performed with another CFRP plate with a thickness of 5 mm and unidirectional fibre orientation. Again, these measurements were performed with three different transducers: a focusing cPP transducer, a non-focusing cPP transducer and a commercially available focusing ACUT transducer. All shown A-Scans are normalized to the same noise level, in order to visualize the Signal-to-Noise ratio (SNR). Compared to the

commercially available transducer as reference, the non-focusing cPP transducer reaches a dynamic range of +15 dB respectively. The focusing cPP transducer even exceeds +20dB compared to the reference. This implies that lower amplification is required with focusing cPP transducers in transmission inspection, so that thicker test objects may be inspected and a higher inspection quality may be reached.



**Fig. 6.** Dynamic range of inspection results: (a) non-focusing cPP transducer (b) spherically focusing cPP transducer (c) NCG500-D19-P50



**Fig. 7.** A-Scans normalized to noise for: focusing cPP transducer (top), planar cPP transducer (middle) and commercially available transducer NCG500-D19-P50 (bottom)

## 6. Conclusions

Spherically focused air-coupled ultrasonic transducers based on cellular polypropylene (cPP) with apertures of 11, 19 and 27 mm were developed. Sound field measurements showed a significant influence of focusing compared to non-focusing cPP transducers. The focal diameter of all focused prototypes was between 2 and 3 mm. The aperture had little influence in the investigated range, but it had the expected influence on the focal distance.

Prototypes of focused cPP transducers were tested on a CFRP plate with inserts representing delamination. Results of cPP transducers were compared to results which were obtained with commercially available focused ACUT transducers. Focussing cPP transducers showed a significantly better lateral resolution than non-focusing transducers. In spite of a smaller resonance frequency, the focussing cPP transducer produced an image with a slightly better lateral resolution than the commercially available one.

Contrast and Signal-To-Noise Ratio (SNR) for all three kinds of transducers were compared. The highest contrast was reached with focused cPP transducers. The SNR measured on a 5 mm thick unidirectional CFRP was 15dB higher for a non-focused cPP transducer and 20dB higher for a focused cPP transducer compared to the commercially

available one. Therefore, focusing transducers based on cPP represent a good potential alternative to commercially available air-coupled transducers based on piezo ceramics.

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