White Paper

Simulation-based Design of Ultrasonic Dual Element Probes

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Abstract
Ultrasonic dual element transducers are known for a very long time. They consist of two angled piezoelectric elements housed in the same case but separated by an acoustic barrier. While one element excites transient waves into a delay line, the other element acts as a receiver for the echoes produced in the component under test. The main advantages of this type of transducer compared to a single-element pulse-echo probe are a better near-surface resolution and a reduced direct back-scattering noise in heterogeneous or coarse grained materials. Numerical time-domain simulations reveal that the ultrasonic wave phenomena in a dual element probe are surprisingly rich and complex which may lead to an unexpected spatial redistribution of energy in the exciting wave front and - as a consequence - to a deviation from the expected exit angle according to Snell's law. Moreover diffraction effects at the interface between the acoustic barrier bridge and the tested component turn out to be very sensitive to small geometrical changes of the delay line which in turn affects the near-surface resolution and the acoustic crosstalk to the receiver channel. In the present contribution it is demonstrated how the described wave phenomena can be used for a systematic design and optimization of dual element probes.

Keywords
Ultrasonics, Dual Element Probe, Numerical Simulation, Wave Phenomena, Transducer Optimization

I. Introduction
Ultrasonic dual element transducers (e.g. [1]) are often used for thin metal sheet testing. They consist of two angled piezoelectric elements housed in the same case but separated by an acoustic barrier. While one element excites transient waves into a delay line, the other element acts as a receiver for the echoes produced by the sheet (defect and back wall echoes). The main advantages of this type of transducer compared to a single-element pulse-echo probe are a better near-surface resolution and a reduced direct back-scattering noise in heterogeneous or coarse grained materials. Numerical time-domain simulations reveal that the ultrasonic wave phenomena in a dual element probe are surprisingly rich and complex. On the other hand, this offers the possibility for a variety of improvements.

II. Methodology
2-D and 3-D versions of the Elastodynamic Finite Integration Technique (EFIT) [2] were used to model the spatio-temporal wave field inside and outside of a typical 5 MHz dual-element probe with a roof angle of 6° (Fig. 1). The delay line is made of Rexolite®, a thermoset, rigid, translucent and lightweight plastic, with a P-wave speed of 2350 m/s. The probe is coupled to a 10 mm thick steel sheet by a thin water film. The P-wave speed in the metal amounts to 5900 m/s. The first surprising observation in Fig. 1 is that the excited pule in the left delay line causes a variety of secondary echoes produced by mode conversion of pressure and surface waves. The continuous mode-conversion P-S at the inner barrier leads to an unexpected spatial redistribution of energy in the primary wave front from the left to the right side and - as a consequence - to a deviation from the expected exit angle according to Snell's law (Fig. 2, left and bottom right picture). Moreover, diffraction effects and guided waves at the interface between the acoustic barrier bridge and the metal sheet lead to an acoustic crosstalk to the receiver channel on the right.

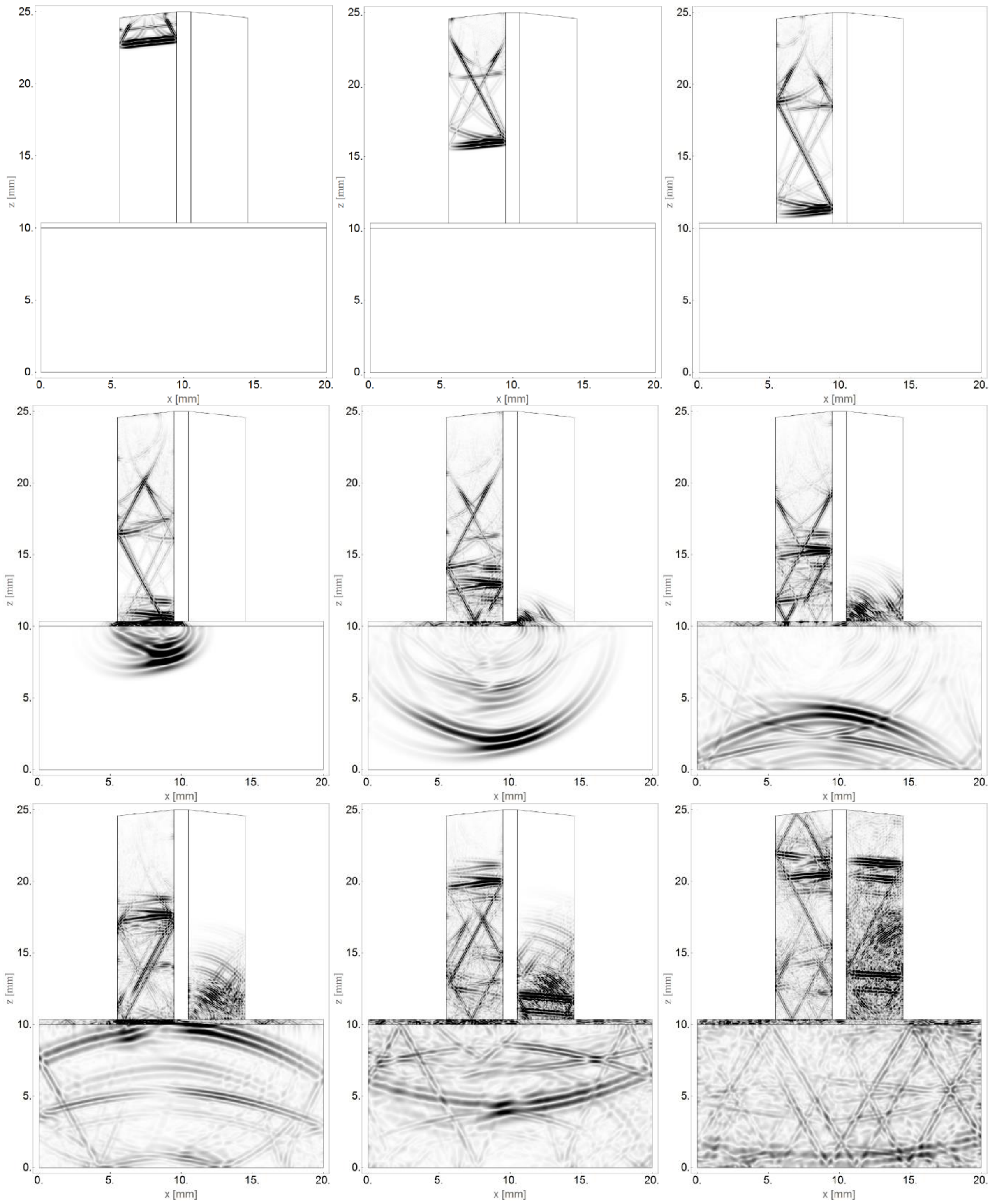

Figure 1: Spatio-temporal wave field of a 5 MHz dual-element probe coupled to a 10 mm thick metal sheet by a thin water film, calculated by the numerical 2D-EFIT method. The roof angle amounts to 6°.

In the present simulation no defect in the metal sheet is existing and thus, only the back wall echo from the bottom surface of the sheet is generated and finally detected by the sensor element in the second delay line (Fig. 2, top right). The first back wall echo is followed by various multiple reflections which are also covered by the EFIT simulation. The evaluation of the transmitted wave field in the metal sheet as depicted by Fig. 2 (left and bottom right picture) shows that the effective exit angle of the main ultrasonic beam in the relevant depth amounts to only 6°. From Snell's Law an exit angle of 15° is expected based on the underlying material combination of Rexolite® and Steel. This large deviation is caused by wave physics and demonstrate that simple geometrical acoustics is not sufficient for the optimization of dual element probes.

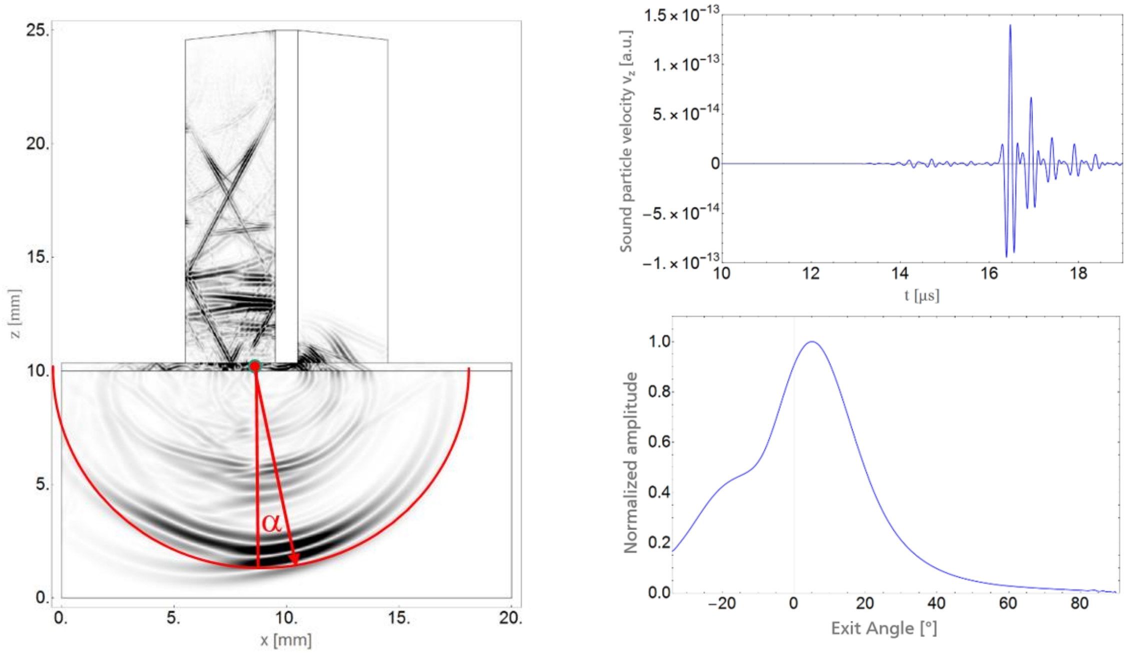

Figure 2: Output of the numerical EFIT model shown in Fig. 1. Top right: Detected A-Scan at the sensor position showing acoustic crosstalk and multiple back wall echoes; left picture: Determination of the directivity pattern of the transmitted wave field in steel; bottom right: Directivity pattern showing an amplitude maximum at an exit angle of 5-6°.

III Defect Interaction and Geometrical Optimization

EFIT models as shown in Fig. 1 can easily be extended to investigate the interaction between ultrasonic waves and various defects. In Fig. 3 a circular scatterer was added to a model of a high-frequency dual element probe with other dimensions but with the same general set-up as shown in the first example. The additional scatterer causes a reflected P-wave and a mode-converted S-wave. However, only the P-wave leads to a strong signal in the second delay line. It arrives prior to the back wall echo and is only slightly affected by the acoustic crosstalk from the excitation channel.

The sensitivity of a dual element probe as a function of depth can be determined by parametric studies where for instance the roof angle or the width of the acoustic barrier bridge between the two delay lines is changed and the resulting echo amplitudes of a defect are evaluated (Fig. 4). In the present example of a high-frequency probe only the depth range between 0 and 5 mm was relevant. In this case a roof angle of 4.5° shows the best compromise between near field and far field performance (Fig. 4, on the left). Also the width of the acoustic barrier bridge between the two delay lines has a significant effect on the depth-dependent sensitivity. Decreasing the width of the barrier bridge improves the near field sensitivity without decreasing the far field sensitivity too much (Fig. 4, on the right). Similar to the examples described above many other parameters of a dual element set-up can be studied and optimized systematically, e.g. the thickness of the coupling layer, the width and length as well as the material and geometry of the delay lines, their inner surface roughness, the frequency, bandwidth and size of the piezo elements etc.

In case of computationally expensive 3-D simulations the direct calculation of wave-defect interactions is omitted and only the deposited energy as a function of sheet depth is studied. In this case only the excited wave field in the delay line needs to be calculated explicitly while the wave field in the metal sheet is obtained by spatio-temporal wave field synthesis [3].

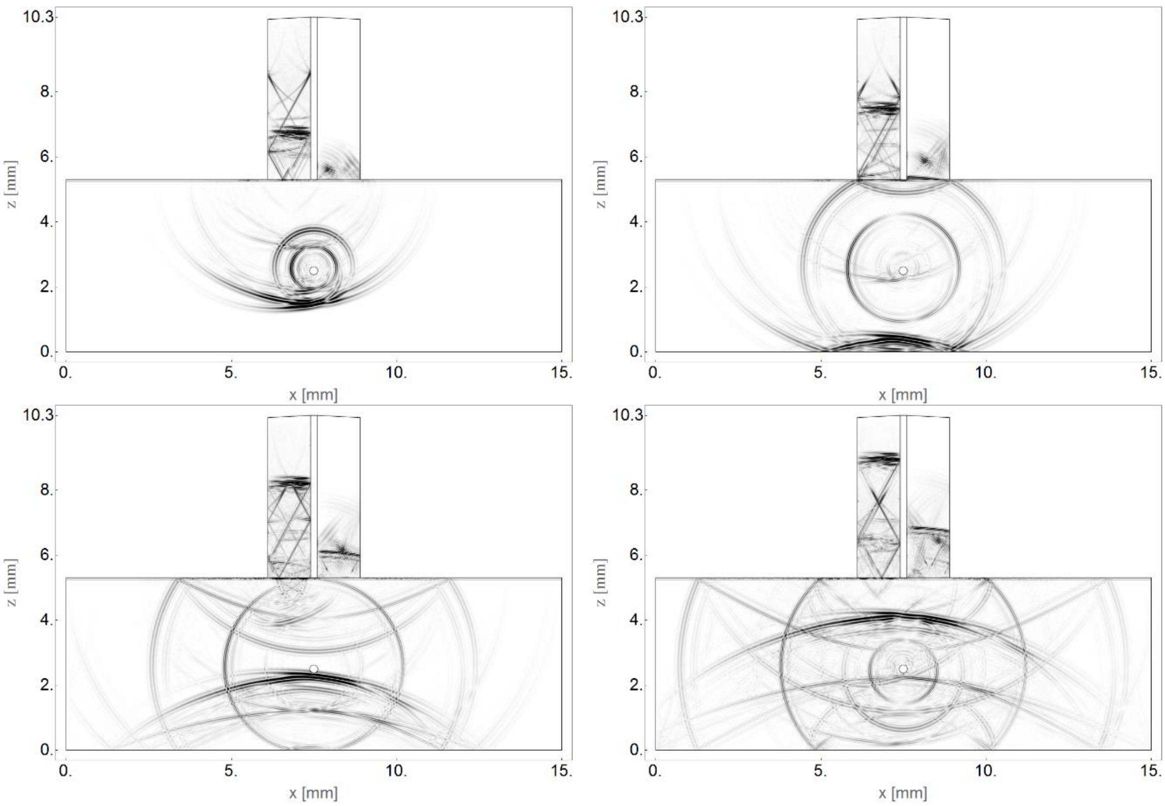

Figure 3: Interaction of the transmitted P-wave with a circular scatterer in the metal sheet.

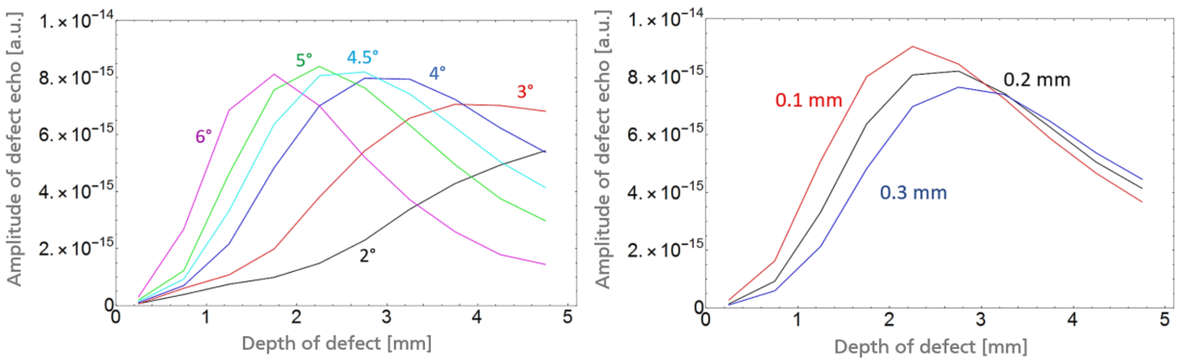

Figure 4: Results of geometrical optimizations. On the left: Sensitivity as a function of depth for different roof angles; on the right: Sensitivity as a function of depth for various acoustic barrier widths.

IV. Conclusion

Wave physical phenomena lead to an unexpected spatial redistribution of energy in the exciting wave front of a dual element probe and to a deviation from the expected exit angle according to Snell's law. Moreover diffraction effects at the interface between the acoustic barrier bridge and the tested component turn out to be very sensitive to small geometrical changes of the delay line which in turn affects the near-surface resolution and the acoustic crosstalk to the receiver channel. In the present contribution it was demonstrated how the described wave phenomena can be used for a systematic design and optimization of dual element probes.

References

[1] *www.sonotec.eu/products/non-destructive-testing/sonoscan-probes/sonoscan-dual-element-probe/*

[2] F. Schubert, *Numerical time-domain modeling of linear and nonlinear ultrasonic wave propagation using finite integration techniques – Theory and applications, Ultrasonics*, 42, 221-229, **2004**.

[3] F. Schubert, B. Lamek, *Fast Numerical Calculations of 3-D Phased Array Wave Fields Based on Transient Point Source Synthesis, CD-Proc. 10th European Conference on Non-Destructive Testing, ECNDT*, Moscow, 10 pages, **2010**.