A Conclusive Concept for Three-Dimensional Imaging Based on Efficient Steering and Focusing of an Ultrasonic 2D-Array

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Abstract. A 16-by-16 element array is operated at a center frequency of 2.25 MHz using a 256-channel transmitter system. Reception is performed with a subset of elements of the array or with a separate single element probe. The beam fields generated in water have been simulated and compared to experiments with excellent agreement. 3D imaging of defects inside components has been addressed only by electronic steering and focusing to various depths of the inspected component. Work has also been done using an 8-by-8 element array.

Introduction

The characteristics of single- or dual-element angle beam transducers can be further improved by operating such probes as phased arrays. These are suitable for a large range of NDT applications, since each of the array elements can be pulsed with appropriate time delays, thus controlling the shape and the sound beam direction on a large scale. Applications where the area of interest can not be properly scanned due to restricted access or where large areas have to be inspected, however, require more sophisticated inspection concepts. In such cases the use of two-dimensional arrays allowing for a three-dimensional steering of the ultrasound beam can be beneficial due to the enormous reduction of the necessary manipulation efforts. In this contribution, we report on results obtained using a16-by-16 element array (center frequency 2.25 MHz) and –quite recently –a 8-by-8 element array (center frequency 1.0 MHz). A 256-channel electronic transmitter system has accordingly been developed to demonstrate the three-dimensional steering capabilities. This phased-array transmitter system has been combined with a standard ultrasonic device. While steering the beam field in three dimensions, reception is performed with either selected elements of the array or with a separate single element probe. The beam fields generated in water have been simulated using a point source superposition technique for various steering and focusing situations, accounting for the proper time delays. These results have been verified by experiments with excellent agreement. Based on these results, the 256-channel transmitter system has been coupled with a standard 16-channel phased-array receiver system. With this combined system the 3D imaging of defects inside components has been addressed only by electronic steering and focusing. The excellent performance of this system will be demonstrated by various experimental results.

This phased array system is aiming at specific applications where the inspection of components with restricted access has to be performed. In such cases, the transducer is placed once with subsequent three-dimensional scanning of the inspection volume of interest, where a combination of beam steering and focusing is used. In the case of large area inspections of thick components the probe is placed at selected positions, thus reducing the number of probe positions without loss of information. Additionally, a considerable reduction of the manipulation efforts can be achieved. In the following, the various ingredients of this system will be described, which are the sensor, the employed simulation approach, the multi-channel electronic devices and the pre-/post-processing units.

1. 16 by 16 Matrix Array Transducer

The sensor consists of 256 elements which are arranged in 16 rows and 16 columns. Each single element is quadratic with a side length of 2.54 mm (1/10 inch), neighbouring elements being separated by 0.1 mm. The effective aperture thus comes up to 42.1 x 42.1 mm^2, the center frequency is 2.25 MHz; Figure 1 shows the sensor with its dimensions. The array has actually been designed to generate longitudinal and transverse waves (using a wedge) in metals. Thus, the beam field structures generated in water are not optimal, with a relatively strong formation of grating lobes at increasing steering angles.

2. Beam Field Simulation and Delay Time Calculation

Beam field calculation is performed using a point source superposition technique, assuming that the transducer is acting as a piston source. The method, which is based on the numerical

Figure 1. Matrix array sensor with its dimensions.

evaluation of a surface integral, is briefly summarized in Ref. [1], while a detailed description can be found in Ref. [2]. Assuming a traction of magnitude zero outside the transducer aperture and unity within, the integration is performed over the transducer aperture. Numerical integration on the basis of an equally spaced rectangular grid is applied, with grid points separated at a distance of less than half a wave length to fulfil the sampling theorem. In considering multiple element transducers, the aperture is accordingly structured with tractions of zero or unity magnitude, respectively, where additionally the proper phase delays to steer and focus the beam field are introduced to each array element. Delay time calculation is performed using Fermats principle. In order to focus the beam field to a certain position, the phasing of the array has to be chosen in such a way that the differences in the time-of-flight of the ultrasonic pulses between the i-th array element and the focal point is given by the minimum value of the corresponding time-of-flight.

3. Experimental Validation Results

To confirm the validity of the simulation approach and to check the sounding performance of the sensor, the beam fields generated in water have been measured for several focusing and steering situations. Figure 2 shows the principal experimental arrangement, where the array probe has been placed at the bottom of a water tank, while a receiving transducer (Karl Deutsch TS6WB2-7, 2 MHz frequency, 8 mm diameter) has been used to perform respective meander-type scanning. Actually, a three-dimensional representation of the beam field has been obtained by acquiring data in various planes at several distances parallel to the transducer surface.

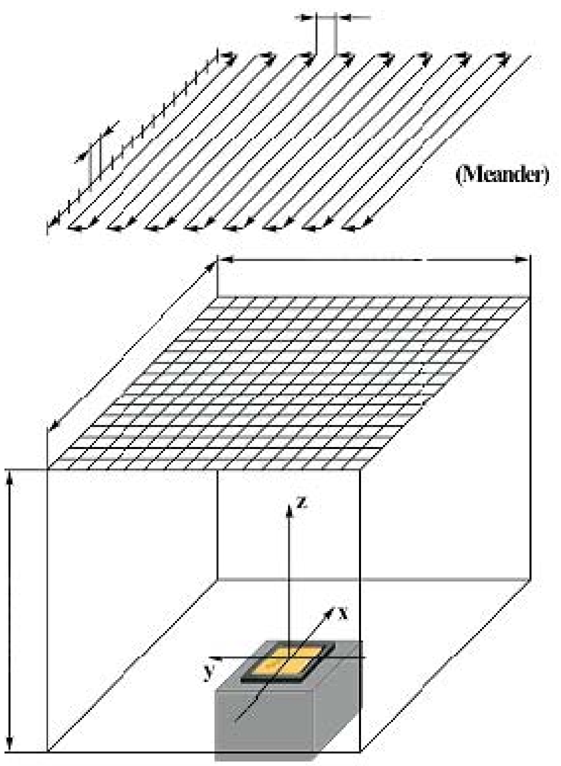


Figure 2. Experimental set-up and scanning scheme used to perform the beam field measurements.

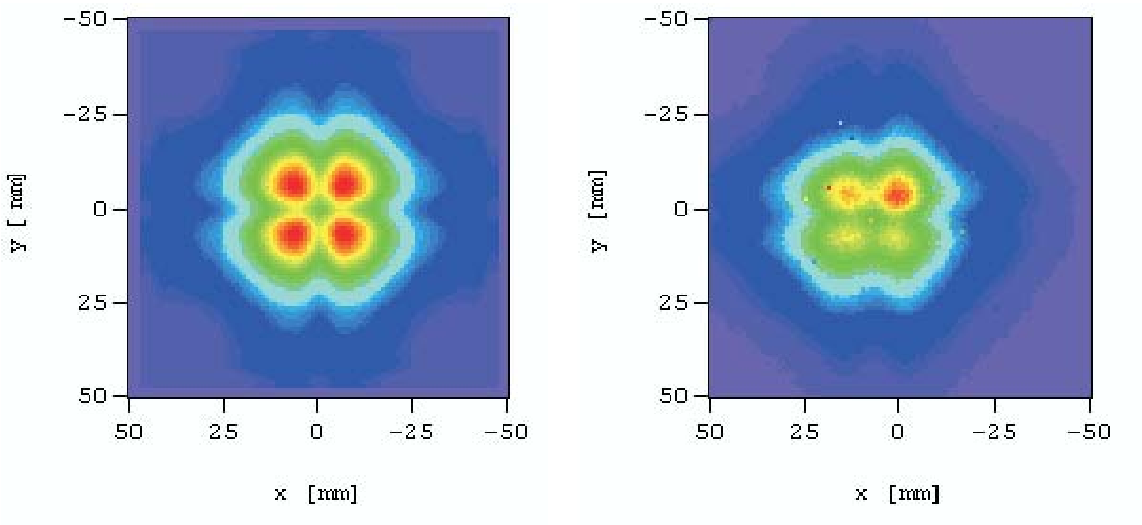


Figure 3. Simulated (left) and experimental (right) C-scan for the case of unfocused, perpendicular transmission, receiver depth 325 mm (half of the near-field length).

In Figures 3 to 5, simulated C-scans are compared with experimental ones, where the characteristics of the receiving probe have been taken into account in the simulation. Both in the case of unfocused, perpendicular transmission (Fig. 3) and in the case where focusing is performed along the acoustic axis to a depth of 108 mm (which corresponds to one sixth of the near-field length, Fig. 4), the agreement is excellent. Slight differences in the results are due to the fact, that exact parallel alignment of the transmitting and the receiving probes has be proven to be a tedious task. In Fig. 5, an example is displayed where focusing has been performed off the acoustic axis, with focal point coordinates being x=20 mm, y=20 mm and z=323 mm. Again, excellent agreement has been achieved.

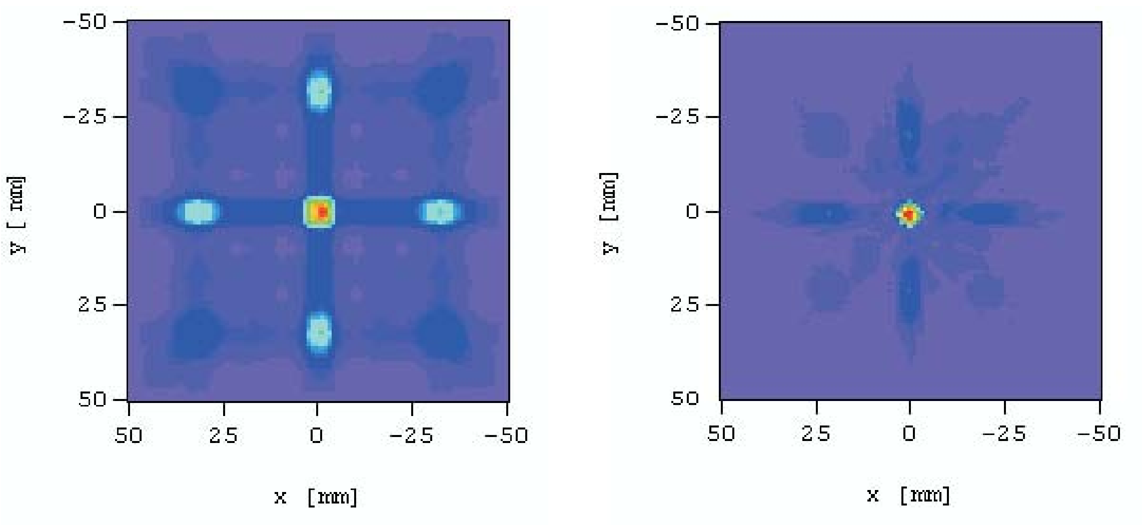


Figure 4. Simulated (left) and experimental (right) C-scan for the case of on-axis focusing to a depth of 108 mm, receiver depth 108 mm (one sixth of the near-field length).

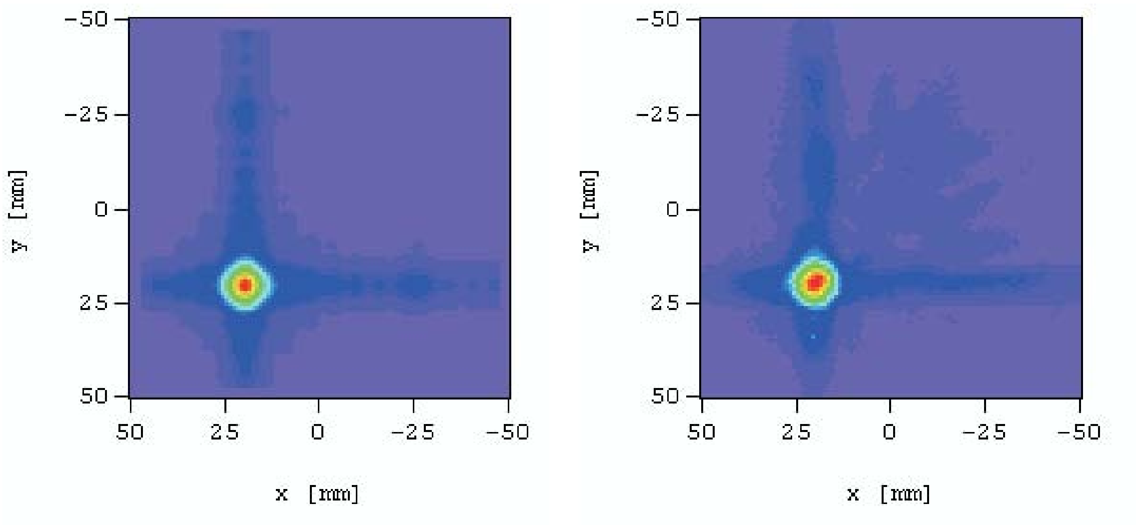


Figure 5. Simulated (left) and experimental (right) C-scan for the case of off-axis focusing to a depth of 323 mm, receiver depth 323 mm (one sixth of the near-field length).

4. Phased Array System - The Modified Concept

The conventional approach of a phased array system in order to perform three-dimensional steering and focusing for a 256-channel matrix array requires a full set of transmitter, receiver, amplifier, acquisition and summation components. This leads to a system with excellent characteristics concerning the beam field in both the transmission and the reception case, at the expense of enormous complexity, large volume, high power and thus extraordinary costs. The new approach presented here makes use of the idea to separate the whole system into two parts: a conventional 16-channel phased array system for the receiving case [3] and an additional unit with 256 phased array transmitters. This means that for steering and focusing in three dimensions the reception is only performed with a subset of elements. Thus, in the ultrasonic inspection procedure a narrow beam field with high energy focusing is used in the transmitting case, while in the receiving case a wider beam field is applied. This concept leads to an inspection system which consists of less electronic parts, thus leading to more reasonable costs.

In principle, the system is controlled by a standard PC. Using various bi-directional, fast synchronous 4-bit interfaces the two parts of the system are programmed and controlled. The transmitter and the receiver systems are coupled by a synchronous serial interface (SSI).The phased array system (ADAPT-US) is a multiprocessor system based on DSP (digital signal processors) and FPGA (field programmable gate array) technology. The phased array transmitter system is also based on FPGA components. In the application under concern the 16 receiver channels were connected to the matrix elements in the center of the probe. The transmitter channels were connected to the remaining matrix elements.

5. Demonstration of the Inspection Performance Capabilities

Similar to a mechanical scan path, the transmitter and receiver delay times for a meander-type scanning are calculated, where focusing is performed along planes in different depths inside the object to be inspected. Thus, the mechanical scanning of a (single element) probe with a fixed insonification direction is replaced by a beam field scanning with the array probe position being fixed. Focusing and steering for each virtual scan position is performed by calculating and programming the proper delay times to the transmitter and receiver channels, while the transmitter is excited according to the virtual scan path. With the current laboratory prototype of the system three-dimensional data acquisition can be realized with a repetition rate of up to 2000 cycles per second, for a fixed array position on the test object. To demonstrate its capabilities, we have performed experiments on several specimens.

Using the 16 by 16 matrix array, electronic scanning with a highly focused beam has been performed on an aluminium block. This block has been supplied with flat-bottomed holes to form a spider-like pattern, which has been drilled at variable depth between 7 mm and 19 mm from the bottom (Fig. 6, lower right). In the color coded C-scan images, recorded at several depths as also shown in Fig. 6, the spider pattern can be clearly recognized. These results have been obtained without any optimization of the location of the receiving elements.

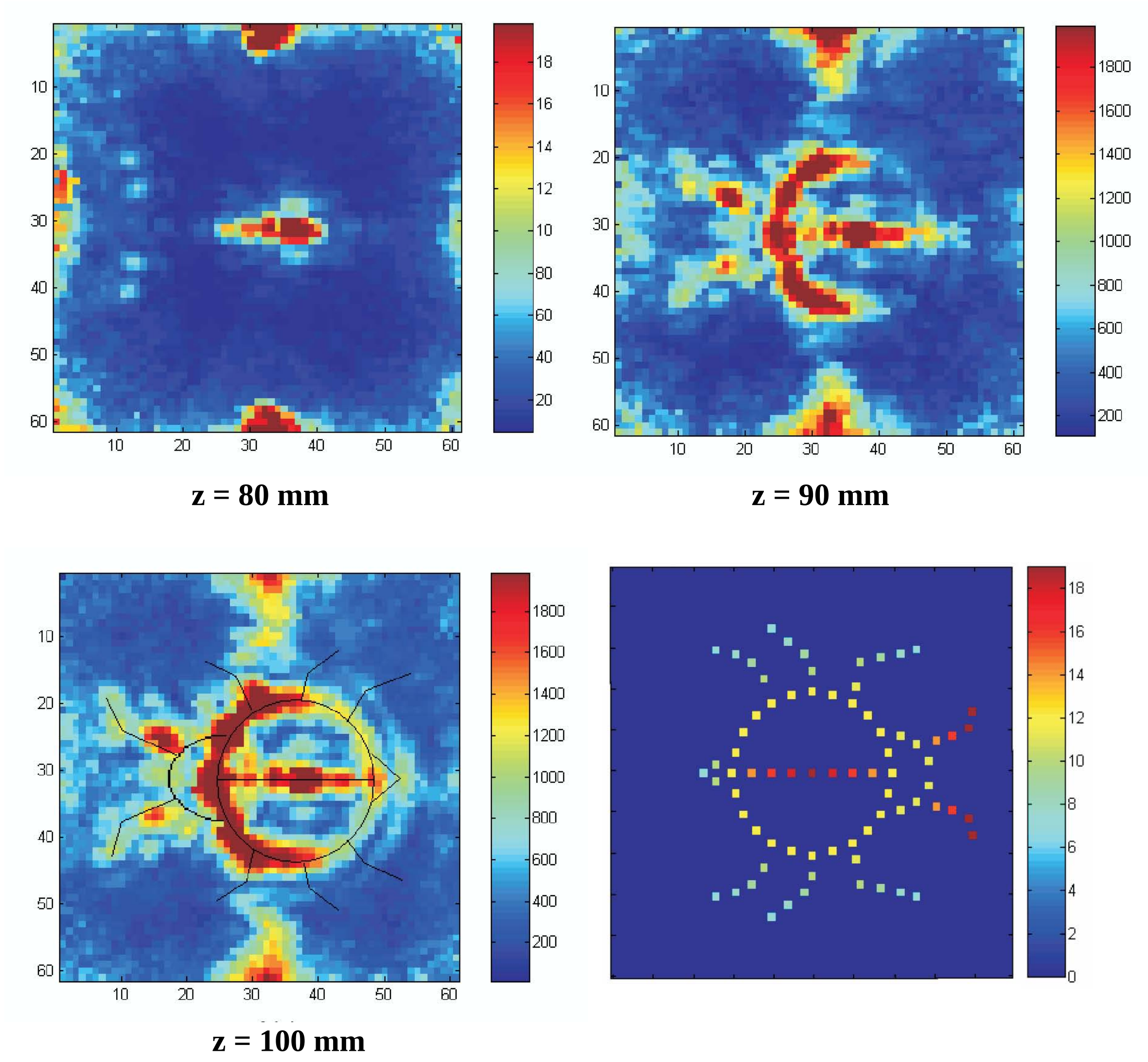
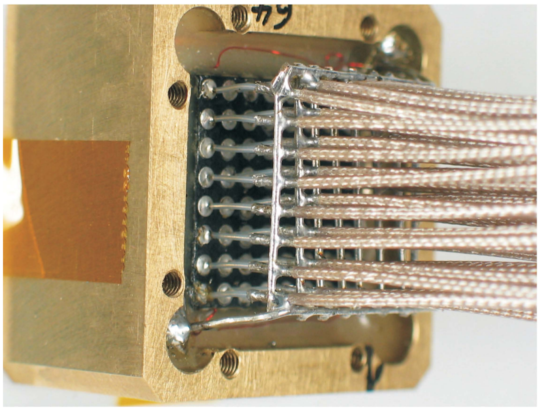


Figure 6. Lower right: spider pattern and depth of the flat-bottomed holes, other: C-scans obtained for different focusing depths z as indicated.



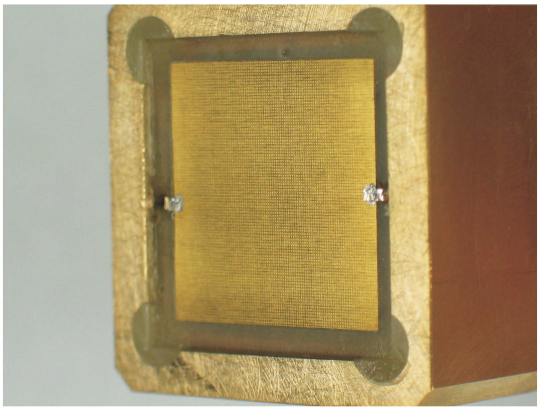


Figure 7. 8 by 8 matrix array for lower frequency applications during fabrication. The cabling to supply the 64 elements is clearly visible.

Depending on the application, the distribution of the receiving elements across the 2D-array might be beneficial, rather than using the 16 center elements for receiving, as in the present case. Here, simulation will provide further information to optimize the set-up.

With this modified PA concept we are also pursuing to improve the inspection performance for (highly) attenuative media, such as e.g. viscoelastic composite materials or coarse-grained metallic components. Aiming at these applications, a second transducer prototype has been developed, operating in a lower frequency range (1 MHz center frequency). Figure 7 shows this 8 by 8 matrix array during fabrication. Each single element is again quadratic with a side length of 2.54 mm and an element-to-element separation of 0.1 mm.

With this probe, first experiments have been performed in view of its lateral resolution behaviour. Figure 8 shows a C-scan image obtained by electronically scanning two side-drilled holes of 2 mm diameter, which are separated by a distance of 5 mm. The probe has been placed onto the component in such a way that the cone-shaped tips of the drillings are insonified at an angle of approximately 45°. Under these conditions, the cones provide the only (reflected) contributions to the detected signal.

6. Summary and Future Work

The combination of a full transmitting system and a reduced phased array receiving system leads to new inspection capabilities for three-dimensional ultrasonic testing and imaging. First experiments have shown the systems potential in order to achieve a high resolution due to efficient focusing. The improved inspection capabilities concern particularly the inspection of complex components (curved geometries), where a mechanical scanning is not possible or would require excessive manipulation efforts. The presented system constitutes a complete solution, including the sensor, the transmitting and the receiving system as well as the simulation algorithms for delay time calculation and beam field modelling. The performed simulations were validated and used to evaluate the performance of the 2D-array probe. Further simulation work is underway to optimize the position of the array elements in the receiving case. Here, the application of a sparse array appears to be most promising, since in the receiving case the appearance of grating lobes is not considered as a drawback.

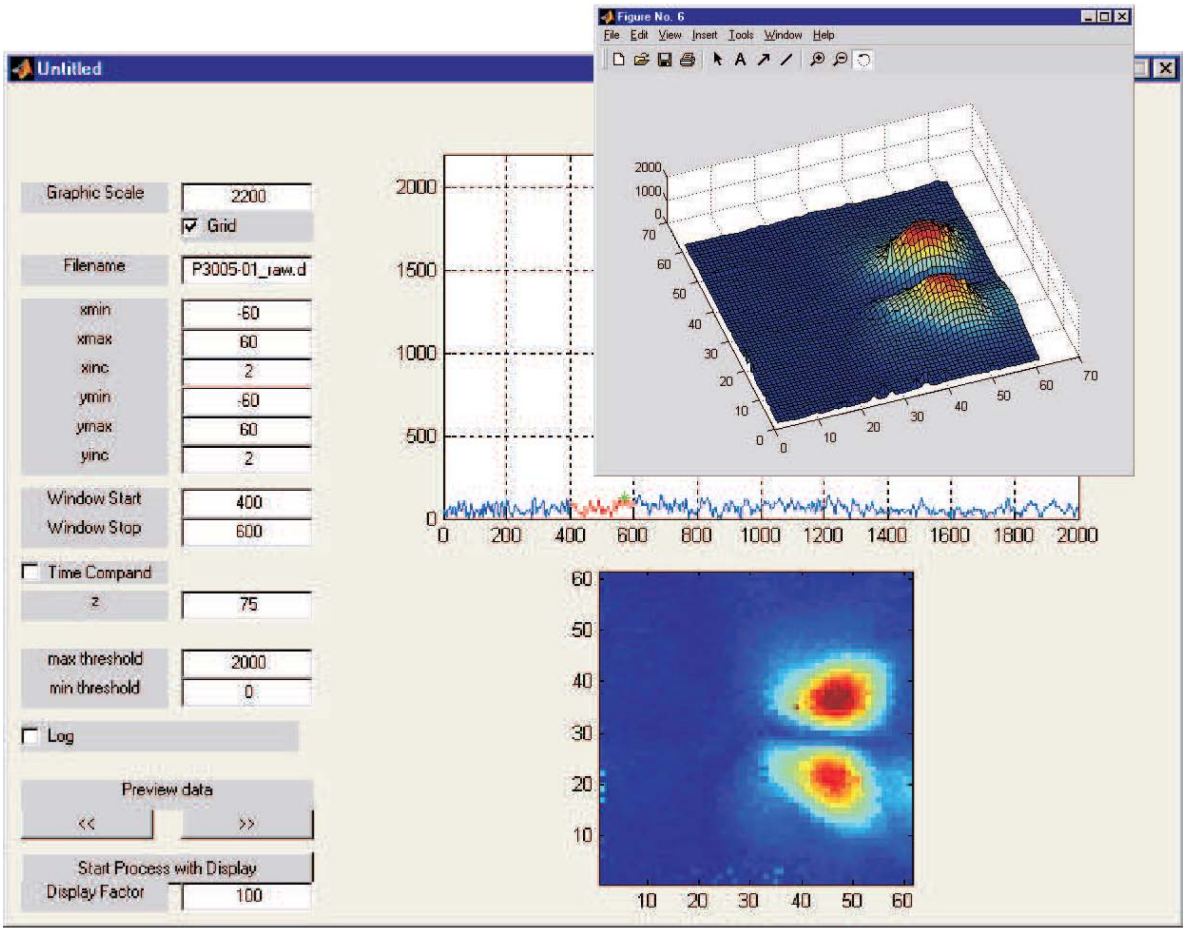


Figure 8. C-scan obtained by scanning two side-drilled holes with cone-like tips (note: the indicated scaling does not correspond to mm). An excerpt of MatLab-environment which allows for a user-friendly handling is also shown.

References

[1] Spies, M., "Modeling Transient Radiation of Ultrasonic Transducers in Anisotropic Materials Including Wave Attenuation," in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D.O. Thompson and D.E. Chimenti, AIP, New York, Vol. 21, 2002, 807-814

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[3] Rieder, H., Spies, M., Licht, R., Kreier, P., "Development and Optimization of a Rotating Phased Array Inspection System," in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D.O. Thompson and D.E. Chimenti, AIP, New York, Vol. 22, 2003, 785-792