Antenna Design and Performance Assessment for fast High Resolution Sonar Imaging using high Bandwidth Transducers and Frequency Domain Compounding

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Abstract- In this work, we present the design and performance assessment of a Multi Beam Echo Sounder (MBES) antenna for fast high resolution sonar imaging as a follow up to a previously presented concept based on high bandwidth transducers and frequency compound imaging. The antenna configuration consists of a modified mills-cross set-up of two linear array transducers with 128 elements each with a center frequency of 1.0 MHz. The elements of the antennas are set-up in a special geometrical assembly for ideal acoustic directivity. Each element consists of the acoustic sandwich optimized for sensitivity and bandwidth on a carrier for highly precise positioning and safe and simple electrical connection.

The antenna performance was tested by means of water tank measurements on test targets. Channel data acquisition was performed using a digital acoustic research platform and beamforming was performed according to the concept presented earlier. The achieved spatial resolution and sensitivity correspond well with the theoretical expectations.

I. Introduction

Ultrasound systems employed in medical imaging are specifically optimized for high acoustic center frequencies and high useable bandwidth. Adaptation of medical transducer design principles incorporating acoustic matching layers, backing optimization and single crystal materials offers possibilities for development of high bandwidth high frequency sonar sensors. High frequency systems reduce the needed antenna dimensions and the large available bandwidth can be used for increasing the temporal/spatial resolution of the imaging system by compounding an image dataset in the frequency domain. The application of design guidelines for element and antenna design of medical ultrasound probes and with this the technology transfer between these fields is one general aim of our work.

In our previous work [1] we described the concept of using high bandwidth transducers for spectral compounding in order to achieve high imaging rates and potentially real time three dimensional imaging capabilities. In order to follow the development path towards this concept, we designed a simplified imaging system, which allows us on one side to implement and test the technology for antenna manufacturing and on the other side achieve valuable information about the potential imaging performance.

II. System Design

Antenna Concept

The simplified system antenna configuration we present in this work consists of a modified mills-cross set-up of two linear array transducers with 128 elements each with a center frequency of 1.0 MHz. While we have focused on a T-configuration of 128 single transmit and 128 single receive channels in the previously presented work we simplified the antenna design in this work to a parallel configuration using one single channel transmitter with a shaped transmit antenna in combination with a 128 single receive channel receiver.

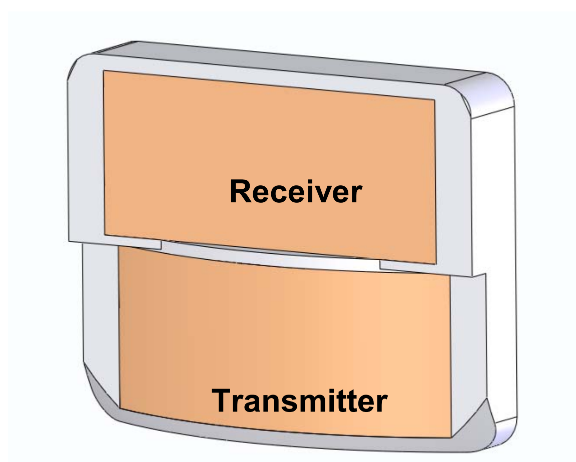

Figure 1. Parallel antenna configuration of transmitting and receiving antenna

The transmit antenna emits a fixed fan-like sound beam into the media with a wide opening angle in the horizontal direction and a focused small opening angle in the vertical direction. The receiving antenna receives the reflected sound signal with 128 single elements. The element signals are used to digitally reconstruct 128 sound beams within the

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transmitted fan-like sound beam. Each reconstructed beam has a fixed focusing in the vertical direction and beamformed focusing the horizontal plane.

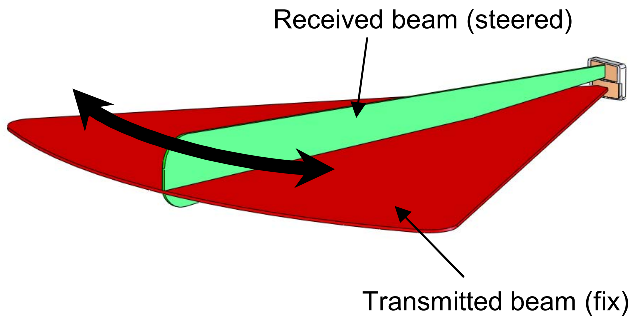

Figure 2. Antenna configuration showing beampatterns and basic functionality

Element set-up
The elements of the antennas are set-up in an optimized geometrical assembly for ideal acoustic directivity. Each element consists of the acoustic sandwich optimized for sensitivity and bandwidth on a carrier for highly precise positioning and safe and simple electrical connection.

Transmitting Antenna
To reduce the number of necessary transmit channels we decided to use a conformal array. The transmitter consists of 128 single element transducers which are driven in parallel. Each element is placed on a conformal carrier which is shaped according the curve shown in Figure 3.

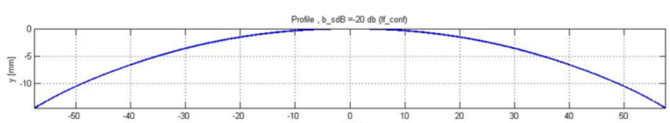

Figure 3. Shape of transmitter and transmitter base in horizontal direction

The shape of transmitter's aperture (and base) was determined by optimization of the resulting beam pattern by simulation of the sound field using in house software tools SCALP. The shape is described with a 8 order polynomial applying the coefficients listed in figure 4.

$$y(x) = x\_2 \cdot x^2 + x\_4 \cdot x^4 + x\_6 \cdot x^6 + x\_8 \cdot x^8 \qquad (1)$$

X_2:	-3.66
X_4:	-583.20
X_6:	251103.47
X_8:	-43150697.58

Figure 4**.** Coefficients for fourth order polynomial of shaping curve of transmitting aperture

The simulated horizontal beam pattern in demonstrated in figure 5. By applying the calculated optimized curve, the simulated -6 dB horizontal opening angle of the transmitter amounts to ±30 °. Due to the technical realization of the antenna shape the actual achieved result differs from the ideal calculated result.

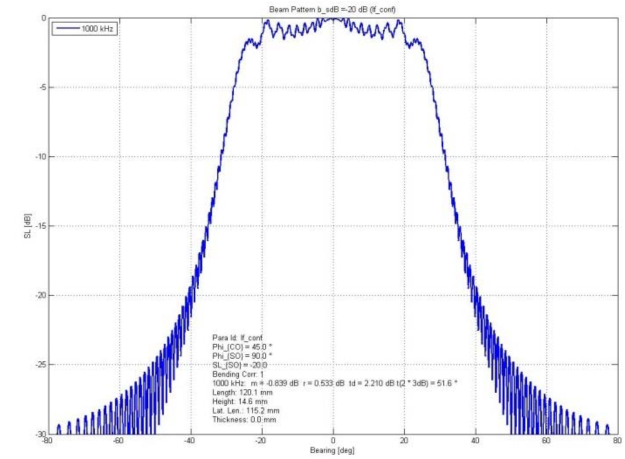

Figure 5. Simulated azimuthal soundbeam pattern of transmitter with shaped aperture

Receiving Antenna
The receiving antenna consists of 128 transducer elements in linear assembly where element is connected to a receiving channel of the beamformer. The elements have a pitch of 0.9 mm (0.6 lambda). The overall dimensions of the receiving antenna are 115 mm x 50 mm. This leads to a strong focusing effect in the horizontal axis of the antenna. The opening angle at 0° receiving angle calculates to 0.7° as shown in Figure 6.

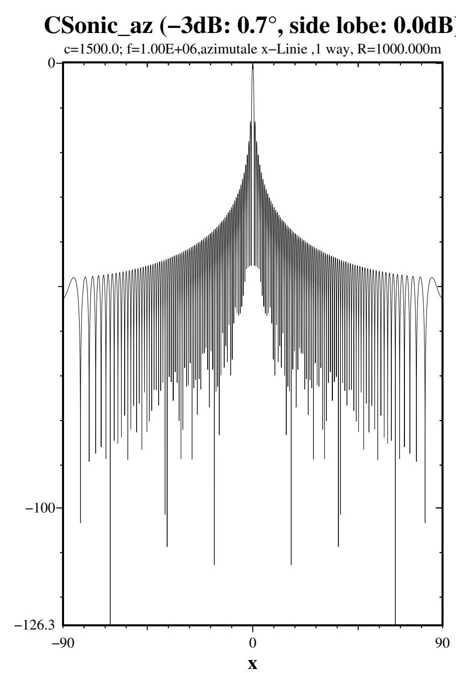

Figure 6. Simulated azimuthal soundbeam pattern [dB] of the receiving antenna under 0° receiving angle

The vertical dimensions of the transmitter and receiver are identical. The vertical opening angle of the sound beam in transmit and receive is shown in Figure 7. The -6 dB opening angle at 0 ° steering amounts to focus of simulates to be 1.5 °.

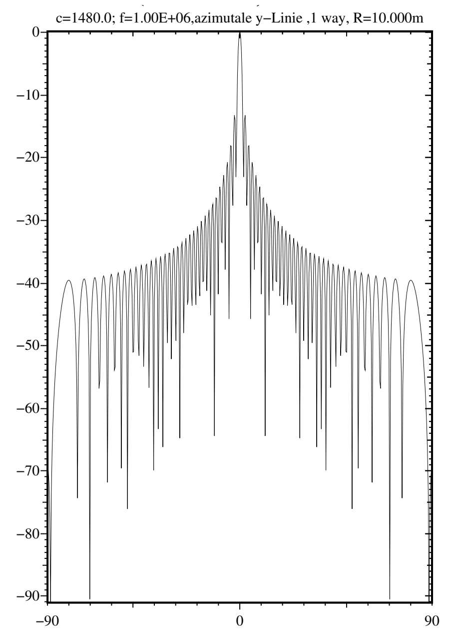

Figure 7. Simulated elevative soundbeam pattern [dB] of the transmitting / receiving antenna under 0° receiving angle

In two-way wave propagation from the transmitter to the receiver the resulting opening angle of the system amounts to 0.75 ° by 0.7 °. Due to the small pitch we also expect good phasing characteristic between ± 30 ° for the receiving antenna. The simulation in Figure 8 shows a simulated sound field with a steering angle of 30°.

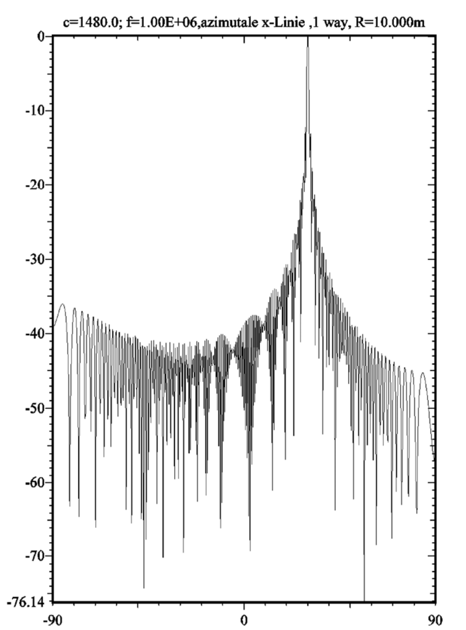

Figure 8. Simulated azimuthal soundbeam pattern [dB] of the receiving antenna under 30° receiving angle

The simulation shows that there is still an acceptable sidelobe suppression of -13.4 dB with no grating lobes at this steering angle.

III. System Realization

The antennas were set up according to the simulation based optimized designs. For each antenna 128 transducer elements with matching layer were built and assembled. For the first performance assessment antenna test samples were built as separated units.

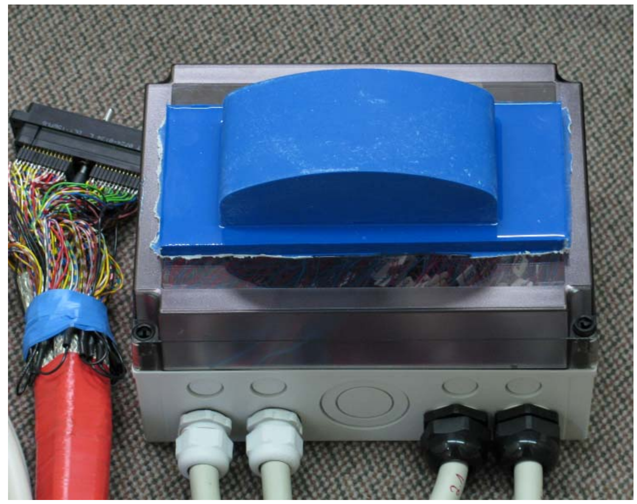

Figure 9. Image of a transmitter test antenna for performance assessment

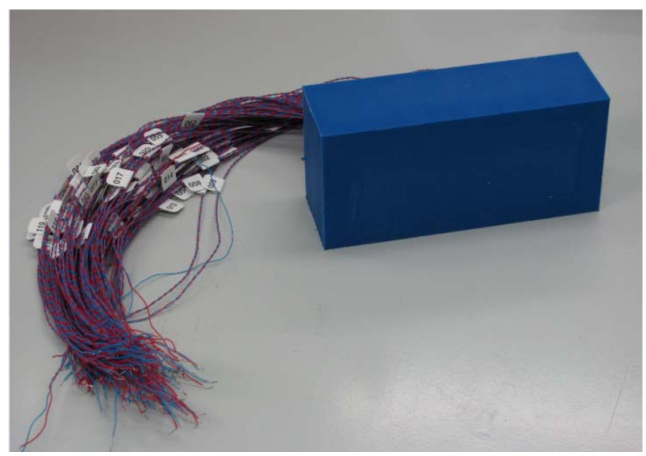

Figure 10. Image of a receiver test antenna for performance assessment

IV. System Performance

The antenna performance was tested by means of water tank measurements on test targets. Channel data acquisition was performed using a digital acoustic research platform and beam forming was performed according to the concept presented earlier. The performance assessment was done in two different environments. A nearfield qualification in a small water bassin was done with the receiving antenna only. In this test transmit and receive beamforming was applied and a test object was imaged. The far field qualification of both antennas was performed in a large water bassin using the MBES functionality of defocused transmitting and beamformed receiving.

Nearfield Qualification
The nearfield qualification was done in a measurement tank with a volume of 1,5 m x 0,8 m x 0,8 m. A pyramid of test target spheres with acoustic impedance of 2,4 MRayl and a diameter of 50 mm was placed on the bottom of the tank and the receiving array was driven in acoustic B-mode imaging with IBMT's digital phased array system (DiPhAS) adapted to the distance and frequency range of the transducer.

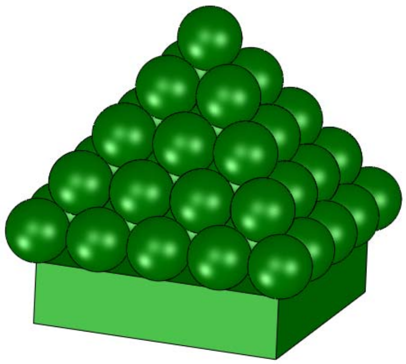

Figure 11. Phantom object (pyramide of reflector spheres (2.4 MRayl, diameter 50 mm) for near field system qualification

The antenna was placed in a shallow incident angle to one side of the pyramid for visualizing a large number of spheres.

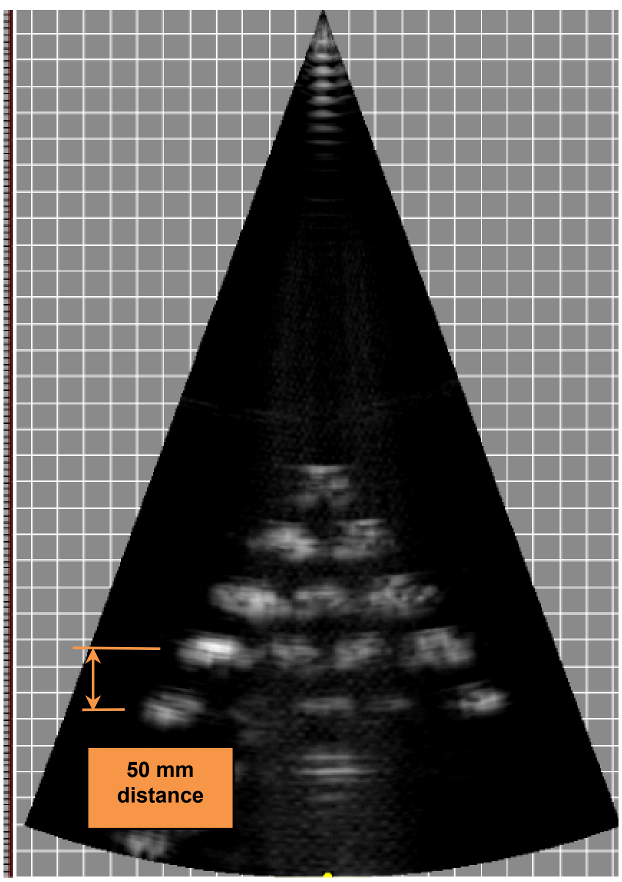

Figure 12. System qualification in B-Mode with receiver antenna (nearfield)

All structures of the object are clearly visible and measured dimensions match the real dimensions of the object. The mid to mid distance of the target spheres could be correctly measured to 50 mm. #+

Farfield Qualification
The far field qualification was done in IBMT's sonar measurement tank with the dimension of 6 m x 8 m x 6 m. Due to the system nearfield length of more than 2 m this tank size is necessary for antenna qualification under MBES operation conditions.

Figure 13. System qualification in measurement tank 6m x 8m x 6m for farfield measurements

The test object used for the farfield qualification consists of a pyramid made of 5 cylindrical discs with 50 mm thickness and diameters ranging from 50 mm up to 450 mm in steps of 100 mm. The discs are made of material with an acoustic impedance of 2.4 MRayl. A schematic of the test object is shown in figure 14.
The object was placed on the bottom of the tank in a distance of 6 m from the antennas which were placed beneath the surface of the water level. All measurements were performed in fresh water at 16° C. Single transmit data was acquired using IBMT's digital phased array system (DiPhAS) running at 5 MHz digitalization frequency. The data was band pass filtered and ingle slice reconstruction was performed with a sum and delay beamforming algorithm working in time domain.

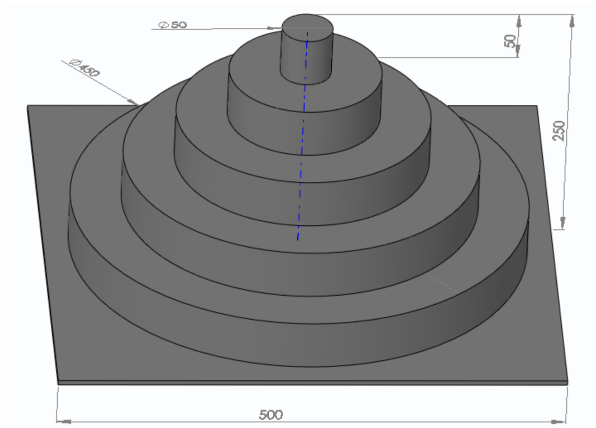

Figure 14. Phantom object for system qualification (farfield)

A reconstructed amplitude image of the gated image in 6 m distance from the transducer is shown in figure 15. Clearly visible are the single disc layers. The layer to layer thickness of 50 mm is correctly measured.

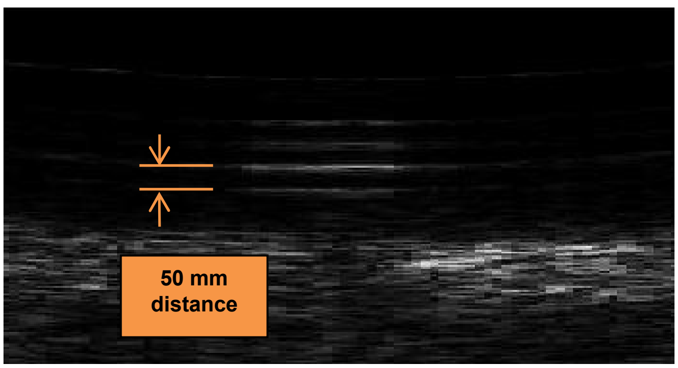

Figure 15. Phantom object for system qualification (farfield)

For threedimensional data reconstruction multiple slices of the phantom were acquired. The transducer was moved over the object in steps of 2 cm and channel data sets were stored. The data processing was performed offline and visualization of the reconstructed slice data was performed using the software package AMIRA (Visage Imaging GmbH, Germany). The reconstructed threedimensional data set is shown in Figure 16.

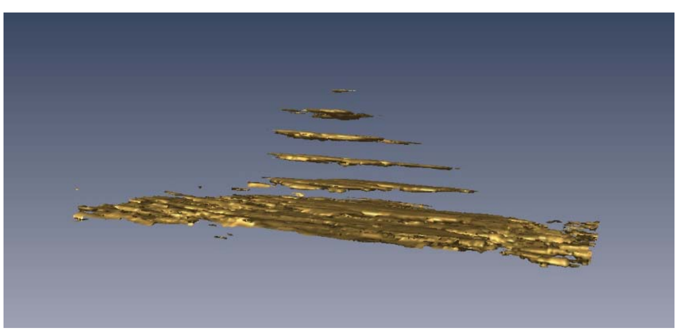

Figure 16. Reconstructed 3D geometry of the disc pyramid measurement object.

All layers of the object are clearly visible in the reconstruction. Also the increasing diameters of the discs are identifiable.

V. Conclusion

In this work we presented the results of the antenna design and performance assessment for fast high resolution sonar imaging. A simplified antenna concept was derived and implemented. Transducer antennas were designed and simulated. Test samples of the antenna were set-up and the system performance was characterized in nearfield as well as under farfield conditions. The designed MBES antenna configuration allows to expect a spot size of approx. 4.5 cm x 4.2 cm in a distance of 6m. A measurement object was placed in this distance and the structures of the object were clearly detectable. The achieved spatial resolution corresponds well with the theoretical expectations. The imaging potential is in well accordance to the theoretical prediction.

VI. Outlook

Our future work will focus on optimizing the antenna and system performance, data reconstruction and implementation of real time beamforming.

Acknowledgment

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References

[1] Towards fast high resolution sonar imaging using high bandwidth transducers and frequency domain compounding, Lemor, R.M.; Becker, F.J.; Degel, C.; Holscher-Hobing, U.; Biegler, H.; OCEANS 2009-EUROPE, 2009. OCEANS '09. 11-14 May 2009 Page(s):1 – 5, Digital Object Identifier 10.1109/OCEANSE.2009.5278106.

[2] A.D. Waite, Sonar for Practising Engineers 3rd Edition