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## Ultrasonic Phased Array Design Study for High Speed Axle Inspection using an Electronically Rotating Beam

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### Abstract

For in-service inspections on wheelset axles with a hollow drilling, mechanized ultrasound inspection systems with single element probes are typically used. The ultrasonic testing in the zones close to the external surface of the railway axles can be realized from the inside of the bore hole, without demounting the wheelset and without dismantling the wheels and the brake discs. The testing system must be able to find flaws in the external surface of the hollow shafts, whose surface lies in the radial-radial plane, these are called transversal flaw. Presently testing systems are used, where scanning is realized in the circumferential direction by mechanical rotation of the probe system in the actual drilling. The phased array probe system, which is presented here, can carry out the rotation scan electronically. The scan can be carried out by simply moving the system forward and backwards through the drilling without mechanical rotation. Manipulation becomes simpler and the inspection time can be shortened considerably. The ultrasonic beam can be inclined exactly and be focused in the plane vertical to the specimen axis.

The probe is designed with help of indispensable simulations using especially designed software developed by BAM. The feasibility and the alignment between the simulated and experimental results were shown in earlier projects reported by Boehm et al. (2006) and Völz et al. (2012). The main task here is to optimize a probe for bore holes with a diameter of 65 mm with an increase in sensitivity and a high spatial resolution. This development will be carried out by use of extensive simulations and result in certain changes of the relevant probe parameters.

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## 1. The task

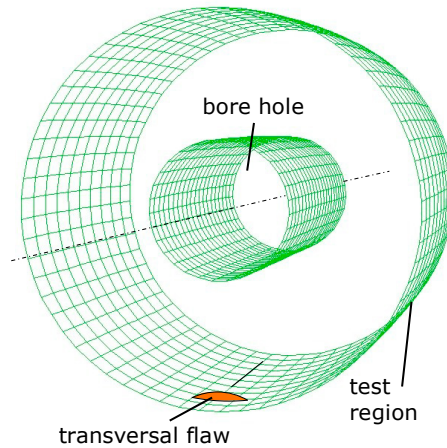


Fig. 1. Position of a flaw in the radial – radial plane, called as transversal flaw

The testing system has to be able to find flaws close to the outer surface of the hollow shafts. The surfaces of these flaws shown in Fig. 1 are positioned in the radial-radial plane perpendicular to the axis of the axle. The ultrasonic testing technique uses the well-known edge effect. Typically the test requires a two dimensional angle-beam scan of the testing zones with conventional angle-beam probes e.g. with a helix like movement of the beam.

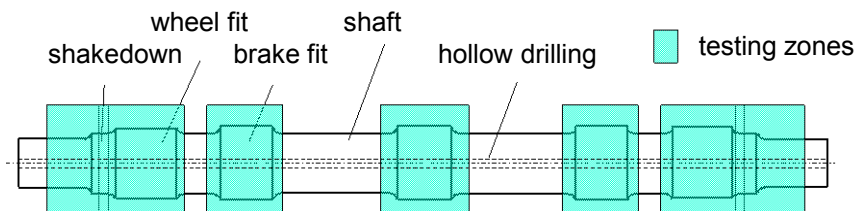


Fig. 2. example of a rail axle with bore hole and test zones

The ultrasonic testing in the zones shown in Fig. 2 close to the external surface of the railway axles with a hollow drilling can be realized from the inside of the drill hole, without demounting the axles and without dismantling the wheels and the brake discs.

## 2. Principle

The principle of the conical rotation scanner for angle beam testing of transversal flaws is shown in Fig. 3. The phased array elements are positioned around the surface of the cone. The beam can be generated in a determined circular direction by using a number of active elements positioned side by side.

On account of the unusual geometry it is unavoidable to perform extensive simulations to understand the acoustic behavior of this kind of array and to optimize the probe design to generate the most adapted directivity pattern.

Fig. 4. shows the collocation of the probe inside the bore hole with its phased array elements, and the calculated directivity pattern in the plane of incidence and perpendicular thereto. The sound field can be focused and the rotation angle can be exactly adjusted by a suitable steering. The coupling medium is oil, which fills the space between the array and the inside surface. The influence of the rotation-symmetrical construction of the probe and of the refraction at the arched inner surface is compensated by the delay time allocation, so that the directivity patterns

originate like they are usually used in the ultrasonic testing. The next step of development in the project WOLAXIM results in a prototype probe system that is illustrated in fig. 5.

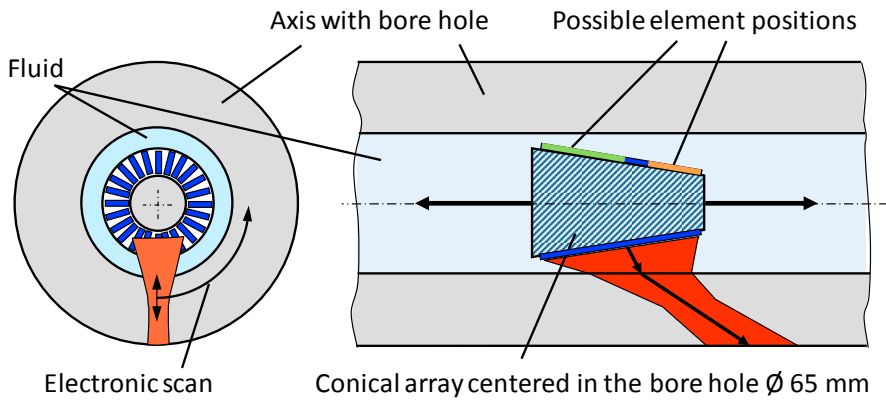


Fig. 3. Sketch of the cone shaped phased array for electronic rotation scan with a focused sound beam

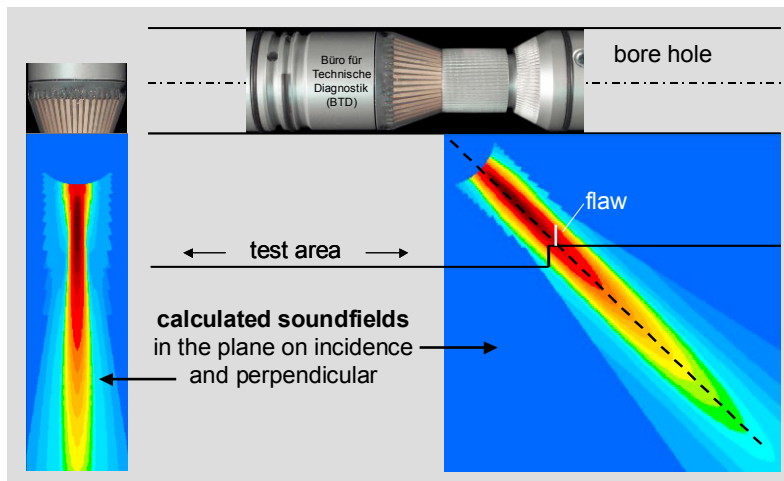


Fig. 4. Calculated sound fields of the first cone shaped phased array, Boehm et al. (2006)

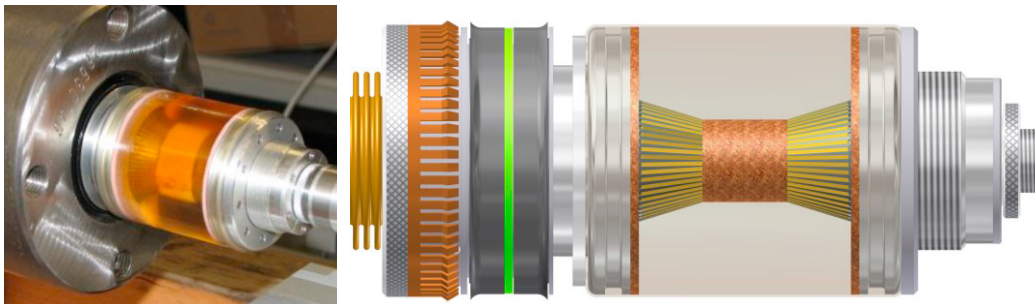


Fig. 5. Probe system from the previous project WOLAXIM, Völz et al. (2012)

### 3. The new development

The main task in the European project “RAAI” is to design a probe with 4 MHz frequency for a high sensitivity and a high resolution. It has to fit in bore holes with a diameter of 65 mm. Additional geometrical boundary conditions are shown in fig. 6. This development will result in significant changes of the probe parameters in relation to the further construction. Prior to the construction of the probe, the optimized probe setup will be evaluated by simulation using semi analytical sound field modeling. The simulation tool ArrayCalculus3D developed by BAM had to be modified for this project to fulfill all the requirements needed to simulate the directivity pattern on coned and curved shapes.

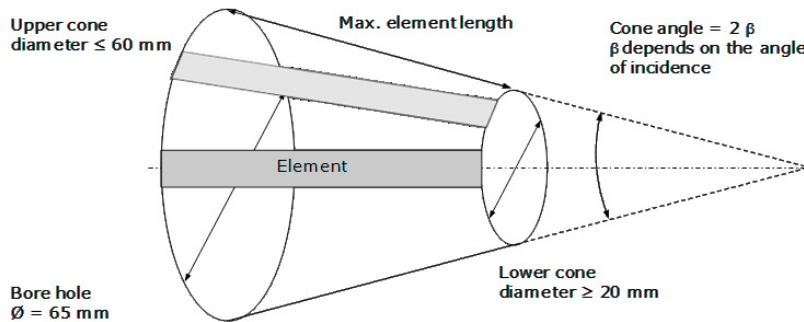


Fig. 6. Geometrical boundary conditions for the new probe

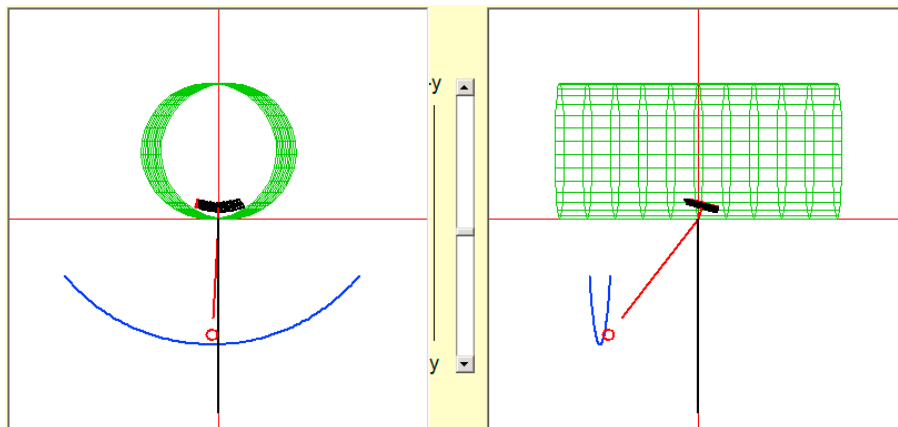


Fig. 7. The position of the array in the bore hole and the line of computation points at the outer surface of the axle

Fig. 7 shows the line of computation points at the outer surface of the axle within the test zones. Fig. 8 shows the dependence of the divergence angle from the element width. Each element with a width of 1 mm delivers a broad ultrasonic beam with a width of  $32^\circ$  at -3 dB amplitude at 4 MHz, see fig. 9. The beam of adjacent elements is displaced by  $3.33^\circ$ . The displacement depends on the total number of elements on the encircling array. In this case the array area incorporates a total number of 108 elements.

The cylindrical coupling surface at the inner bore hole operates as a cylindrical diffusion lens caused by the quotient of the sound velocities. Additionally the geometry results in a rotation-symmetric sound field with an angular range that corresponds with the angular range of the array itself, if all elements are shot simultaneously.

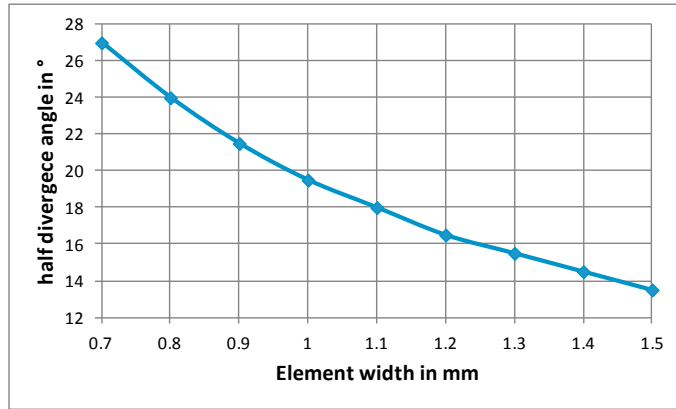


Fig. 8. Dependence of the divergence angle at -6 dB of the single element for a 4 MHz shear wave in steel

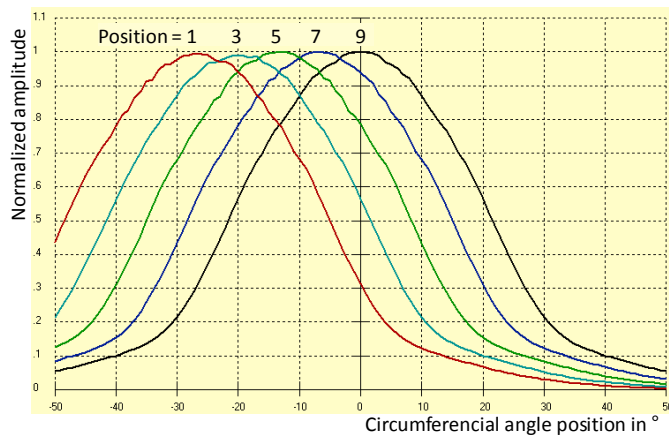


Fig. 9. Directivity of single elements, position in the array of with 17 active el. from 108 el. in total

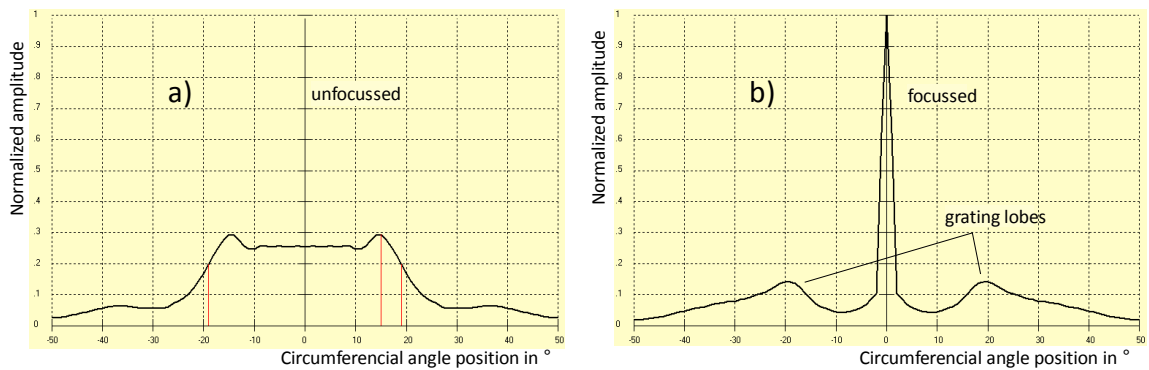


Fig. 10. Directivity of the array with 13 active el. from 108 el. in total, a) unfocussed and b) focussed

The example in fig. 10 a) shows an angle of 38° at -3 dB using 13 elements of 108 / cycle. A focal law calculated using the principle of Fermat allows to focus the ultrasonic beam shown in fig. 10. b). The focusing results in +12 dB higher amplitude. This implies a +24 dB higher echo height for small reflectors. The grating lobes are generated

by the large element pitch in the region of the outer diameter of the cone. Caused by the cones design, echoes coming from the grating lobes have low amplitudes (-34 dB) in relation to the main echo and a constant angular distance to the main echo.

The number of active elements has an influence on the directivity pattern, the amplitude and the spatial resolution.

The amplitude arises with the number of elements lying side by side. However the part of the amplitude, respectively the part of the echo height, becomes smaller towards the edges of the active area and depends on the distance to the middle active element, see fig. 11. a) and b). Fig. 12 shows the arising amplitudes which are not linear to the number of active elements.

Additionally, the beam divergence (bw) becomes smaller with a higher number of active elements. The beam divergence as a function of the number of active elements, is shown in fig 12.

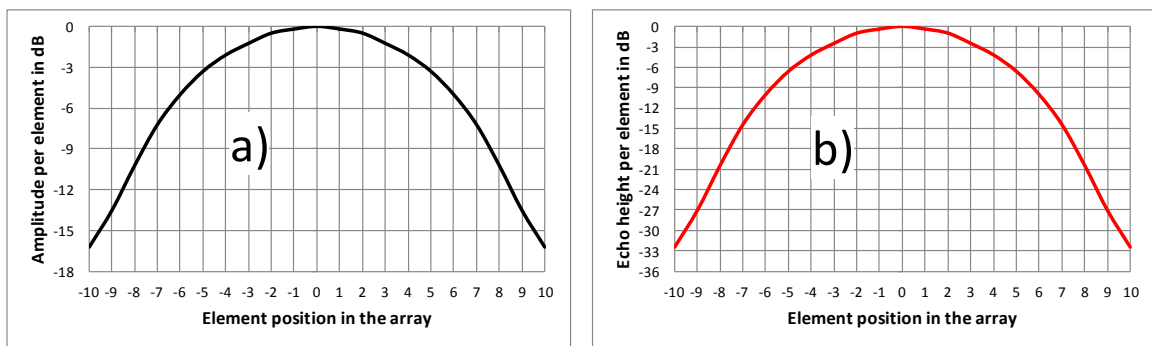


Fig. 11. Amplitude per element in relation to the middle active element of the array dependent from elements position

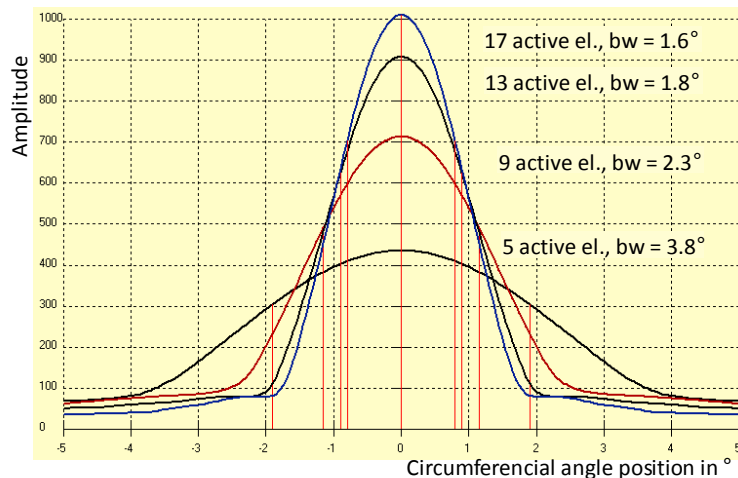


Fig. 12. Amplitude and ultrasonic beam width (bw) as a function of the number of active elements

The element length determines the near field length in the plane incidence, this is the axial-radial plane of the axle. In our example the test region is within the near field length, if the element length is larger than 15 mm. that delimitates the maximum sensitivity and the spatial solution in the axis direction, see fig. 13. and fig.14. A possible solution is to focus the sound beam additionally by bending the elements in the plane of incidence.

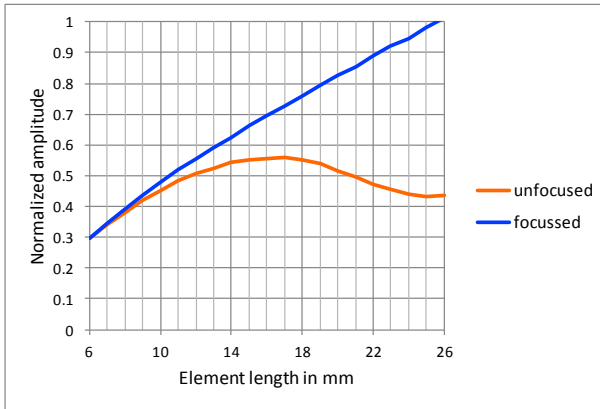


Fig. 13. Amplitude as a function of the element length

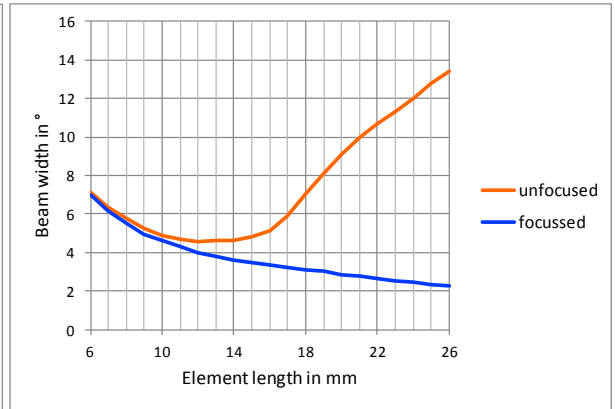


Fig. 14. Beam width as a function of the element length

For the rotational scanning the sound field has to rotate around the cone. Therefore a beam of a 17 active elements array focused on the axle surface with a divergence of  $1.8^\circ$  (- 3 dB) in circumference direction is used. The main rotation of the sound field is realized by shifting the group of active elements electronically in steps of one element. The angle step is  $360^\circ/108 = 3.33^\circ$  per element step, that is bigger than the beam width, see fig. 15. It is necessary to perform additional intermediate angle steps ( $< 1^\circ$  if required) by focal law steering that allows a gapless scan in the circumference direction.

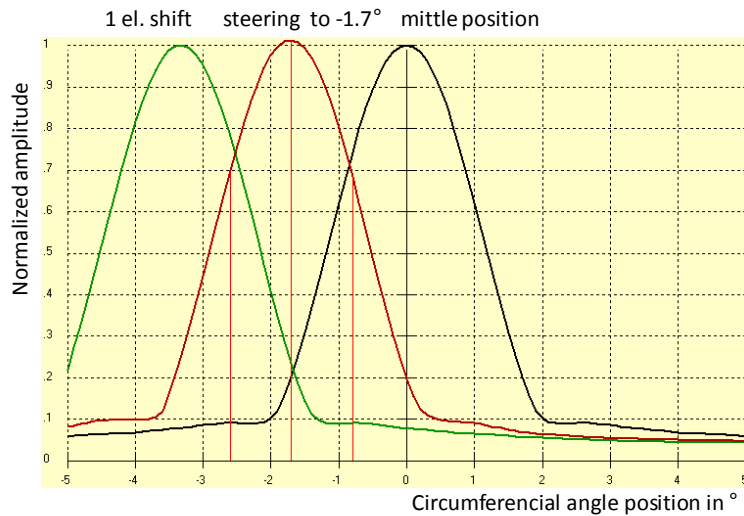


Fig. 15. Circumferential angle position of the focused beam

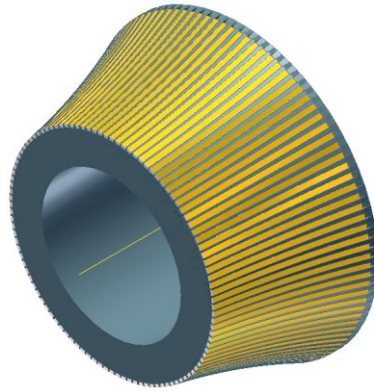


Fig. 16. Idea of the new design of the rotation symmetric phased array on a 2-dim. curved conical surface

Fig. 16 shows the drawing as the preliminary result of the new designed rotation symmetric phased array on a two dimensional curved conical surface.

#### 4. Conclusion

A rotation scanner phased array system has been developed and set up in principle for the ultrasonic testing of axles with hollow drillings from the inside of the bore hole, without demounting the wheelset and without dismantling the wheels and the brake discs and without mechanical rotation of the probe system. This simplifies the manipulation system and the time consumption for the scan process would become significant shorter. The feasibility and the alignment between the simulated and experimental results were shown in the past.

The new task is to optimize a probe for bore holes with a diameter of 65 mm with an increase in sensitivity and a high spatial resolution. The simulation results of the most significant parameter variations are shown in this paper. Especially the influence of the element dimensions, the number of active elements and its influence on the beam width and sensitivity and the focusing in two dimensions are discussed.

During the next steps of the project a probe with optimized parameters based on the developed design will be build and tested on wheelset specimen. Signal processing algorithms for flaw detection and flaw analysis will be developed and tested.

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