Optimization of Curved Broadband Arrays for Pipe Inspection

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Abstract. The paper deals with optimization of controlling mode of a curved phase-array for pipe inspection. It demonstrates the insufficiency of geometrically determined controlling modes. Thus for example, a focusing at 15 mm is in reality a compensation of the array curvature. The paper investigates the existence and the magnitude of grating lobes, limitation of the steering angle and the side lobes caused by element orientation. The limitation of the steering angle and the side lobes are more crucial problems than grating lobes. The paper suggests an adaptation of controlling by means of a fast approach to calculate the sound field.

1. Introduction

In NDT, phased arrays are applied for example to inspect railway wheels, half-finished products or pipes tested in immersion technique. Sound field calculations are necessary for the optimization of the geometrical parameters as curvature, aperture size and element number well as for the optimization of delay times for steering and focusing**.** These calculations have to take into account the differently layered materials and the orientation and curvature of interfaces, which refract, focus and defocus the sound field.
Harmonic calculations to optimize the array size and shape, and to adapt the delay times for non-planar ultrasonic linear arrays used for the inspection of pipes are given in Köhler [1] and Rieder, Spies et all [2].

2. Theoretical Approach

In previous works, two fast approaches are introduced to optimize the parameters of broadband transducers for multilayered complex structures; one is applied to simulate the time harmonic sound field and the other one to simulate the transient sound field for broadband excitation. It is demonstrated that there is only a small difference between the transient sound field and the time harmonic sound field at center frequency of the broadband transducer [3]. Therefore it is possible to optimize transducers for NDT-problems by simulating the time harmonic sound field. The transient sound field is calculated for evaluation only. In this paper, this kind of approach is applied for optimizing broadband ultrasonic arrays.

The approaches, which are based on GREEN's functions, are described in [3]. For the simulation of the emitted array field, this procedure is used to calculate the displacement and the stress of the particular elements of the array, which might be either plane or curved. Hence, the array elements are not considered as single point sources but as three-dimensional areas. All single elements are therefore covered by point sources with a space of a fifth of one wavelength. The field of the whole array is calculated by a superposition of delayed fields of all elements. This superposition is arranged according to controlling mode, whereby the time delay of the particular elements is taken into account by a phase shift. The particular element fields are stored, so that less computing time is necessary for the optimization of time delays. The stored fields can be used for the simulation of various angle scans and modes of focusing.

3. Description of the Measurement Setup

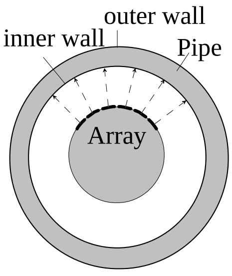


Figure 1. Curved Array

The array is curved and applied for pipe inspection (Fig.1). It has a center frequency of 10 MHz, 8 elements with a length of 10mm and a width of 0.3 mm ($\lambda/2$ regarding to steel). The elements are arranged on a cylinder with a diameter of 7 mm and with a grating distance of 0.33 mm. The inner pipe wall has a radius of 6.6 mm. It is noteworthy that the pipe inspection system contains of 68 elements placed around the entire cylinder. For inspection, only 8 elements work as an array at one time.
The curved array emits a defocused sound field into water. For the pipe wall is curved, the sound field is focused by transmission from water into steel. By means of controlling, the array curvature can be compensated and the sound field can be additionally focused and the focus location can be thereby varied inside the pipe wall**.** Sound fields for three different controlling modes are discussed in Fig.2 to 4. The geometrically determined controlling modes are

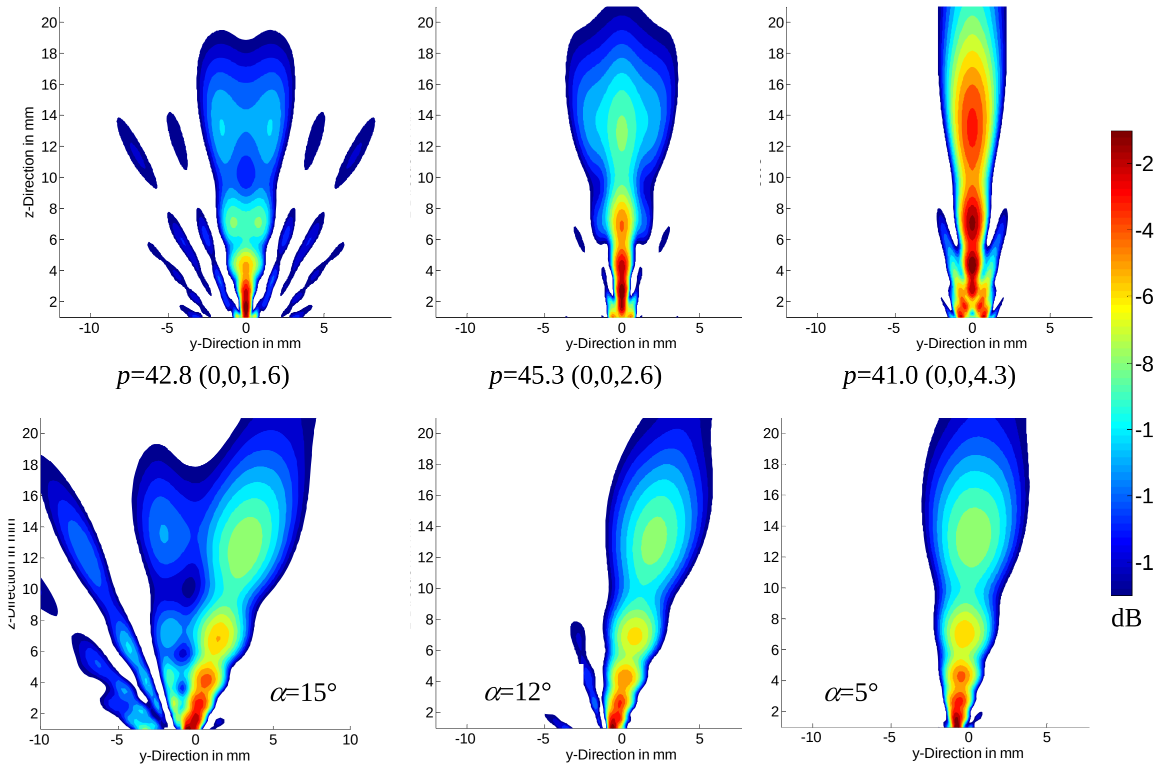
- compensation of array curvature – Controlling C
- compensation of array curvature and focusing at z=15 mm in water – Controlling F15
- incomplete compensation of array curvature – Controlling D

To explain the real effect of controlling, the sound field is separated into two sound beams emitted by the left and the right array-half. In this way, we can see the direction of semi-array beam and thereby we can estimate a possible crossing of the two beams and their cross point. For instance, this yields to an explanation of the earlike appearances in Fig.2a and 5c and of the divergent sound fields in Fig.4.

All following Figures show the longitudinal sections of the sound field inside the water delay or either inside the pipe wall for the whole array as well as for the left semi array. The coordinate system is placed on the last interface so that, inside the water delay, the z-coordinate represents the distance to the array and inside the pipe wall the distance to the inner wall. The interface to the next layer is neglected to observe the location of the sensitivity zone and the divergence of the beam in the layer concerned. In some figures the normalized maximum *p* is given including its location. Inside a figure, the given *p*-values of different longitudinal sections may be compared conveniently.

4. Problematic Aspects of Array Controlling

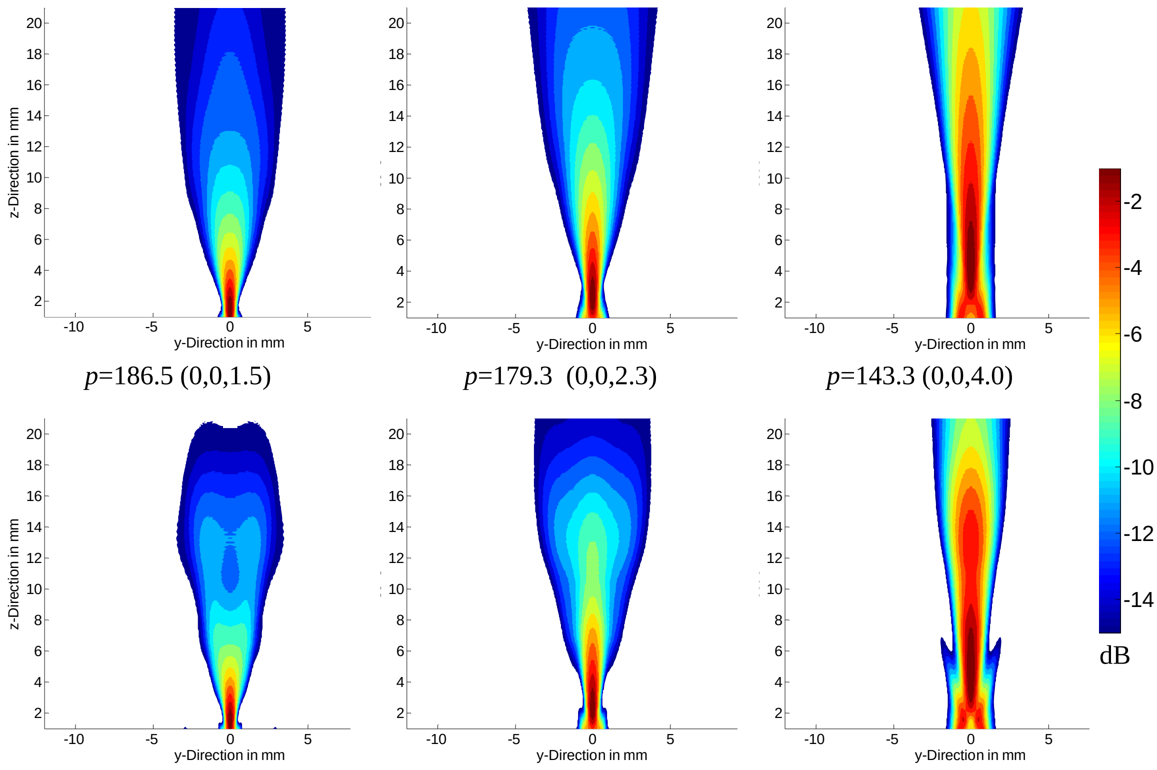
Fig.2 demonstrates that the focus can be located at different places inside the pipe wall. Fig.3 displays the corresponding transient fields. The controlling modes described above are determined geometrically. The controlling F15 (Fig.2a) has a focus near the inner pipe wall and is sufficient for testing close to it. However, there are off-axis structures beyond the focus. Therefore, this controlling might cause double readings and is hence improvable. Such an improvement is only possible by sound field calculations. Since there is a good agreement between transient and time harmonic sound field at center frequency (compare Fig.2 and 3), the harmonic field is sufficient enough for discussion.



p=42.8 (0,0,1.6) *p*=45.3 (0,0,2.6) *p*=41.0 (0,0,4.3)

a) Controlling F15 b) Controlling C c) Controlling D

Figure 2. Time harmonic sound fields of a curved array (8 elements, frequency f= 10 MHz) in pipe wall for different focusing modes top: whole array, bottom: left semi array (first 4 elements)



p=186.5 (0,0,1.5) *p*=179.3 (0,0,2.3) *p*=143.3 (0,0,4.0)

p=176.0 (0,0,1.4) *p*=172.7 (0,0,2.3) *p*=139.9 (0,0,4.3)

a) Controlling F15 b) Controlling C c) Controlling D

Figure 3: Transient sound fields of a curved array (r=3.5mm, 8 elements, frequency f_M= 10 MHz) in pipe wall for different focusing and different excitation functions top**:** 2 periods, bottom: 5 periods

There are different problems that can lead to incorrectness features:

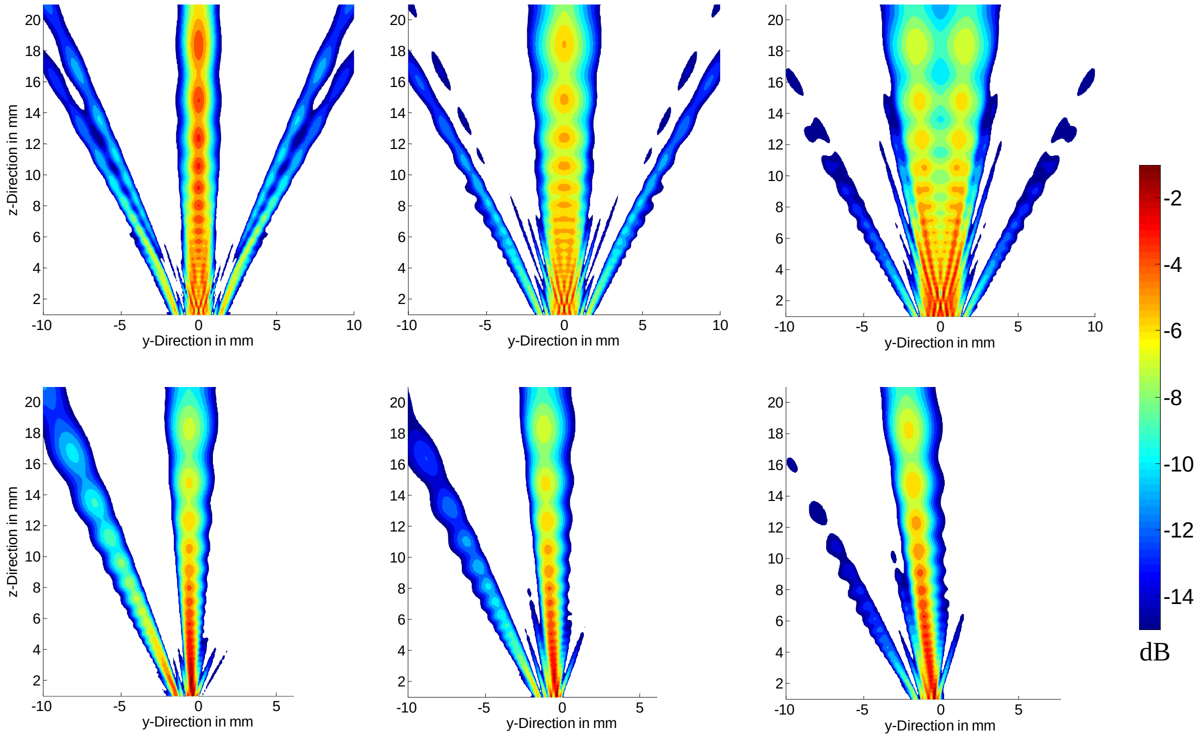
1. Grating lobes
   In steering mode, the array acts as a grating and therefore grating lobes can appear. Calculations of time harmonic sound fields of a plane array show that the angle of the grating-lobe depends on the ratio of the wavelength to the grating distance λ/g only [4]. The magnitude of grating lobes increases with an increasing steering angle. If the element width is smaller than $\lambda/2$, no grating lobes appear, even not for large steering angles. Since grating distance is $\lambda/2$ with respect to steel, no grating lobes should exist in the pipe wall. However, there must be an energy loss of the transmitted sound field caused by the grating lobes in water delay.
2. Limitation of steering
   There is a limitation of steering angle, since two wave trains of neighboring elements neutralize each other in case their delay time difference lasts a half periodic cycle. This results in the following rules:
   - smaller elements need smaller delay times to reach the same steering angle as larger ones
   - the maximal possible steering angle increases with smaller elements

   Sound field calculations has shown that a maximum delay time difference of a half periodic cycle is only a guiding value and that this value has to be diminished if the elements are larger than $\lambda/2$ [5, 6]. Thus, the possible steering angle additionally decreases for larger elements. In the focusing mode, the limitation of steering can cause too small steering angles especially for the peripheral elements. That means that the beam of the fringe elements are not steered effectively enough and do not cross at the focus. To avoid this, the element width should be $g \leq \lambda/2$.
3. Geometrical determined delay times for steering
   Geometrical calculations to determine delay times are a good starting point, but sound field calculations reveal that the angle of the emitted sound field might deviate extremely from the steering angle geometrically determined in advance. The steering error can be in the range of 20° [5, 6]. Therefore, the fitting of delay times should always be checked by means of sound field calculations.
4. Curved Array
   Elements of a curved array do not emit in steering direction and a perfect focusing or steering hence can only be reached by a point-sized element. The partial elements emit normally and thus the sound field becomes more divergent by larger elements. For convex arrays, this effect is even more influential.

Since the incorrectness features 1, 2 and 4 increase with an increasing element size regarding to wavelength, the $\lambda/2-$ condition should be kept. Although this is realized for the test object (pipe wall), the array emits firstly into water and the wave trains of the single elements in fact are steered inside water. Therefore, the element distance of 2λ with respect to water governs the quality of controlling. Since the quality of controlling can be examined easier before transmission into the inner pipe wall, it is reasonable to base further investigations on the sound fields emitted into water.

Fig.4 displays the sound fields for all three controlling modes in water. With controlling C, the two sound beams of the semi-arrays are directed outwards (Fig.4b) and, thus, the resulting sound field of the whole array has a wide beam with two main structures in the near field (Fig.4b above). Inside the pipe wall the beams of the semi-array are directed inwards (Fig.2b) which is caused by the focusing effect of the inner pipe wall.

With controlling F15, the single beams emit in z-direction and parallel to each other. The resulting sound field of the whole array owns one main structure only (Fig.4a). Moreover, it is against expectations unfocussed. That means, controlling F15 just compensates the array curvature (as actually expected of controlling C). Nevertheless, the inner pipe wall focuses the sound field after transmission through water delay (Fig.2a). The two beams of the semi-array are steered strongly inwards. This results in a focus near the inner pipe wall at z=1.4mm. The ears (more apparently for the stronger steering in Fig 5c) are the left and the right beam above the crossing. Controlling D in contrast is more sufficient for testing in heavy pipe walls. However, because of the more divergent sound field, the resolution decreases.



a) Controlling F15 b) Controlling C c) Controlling D

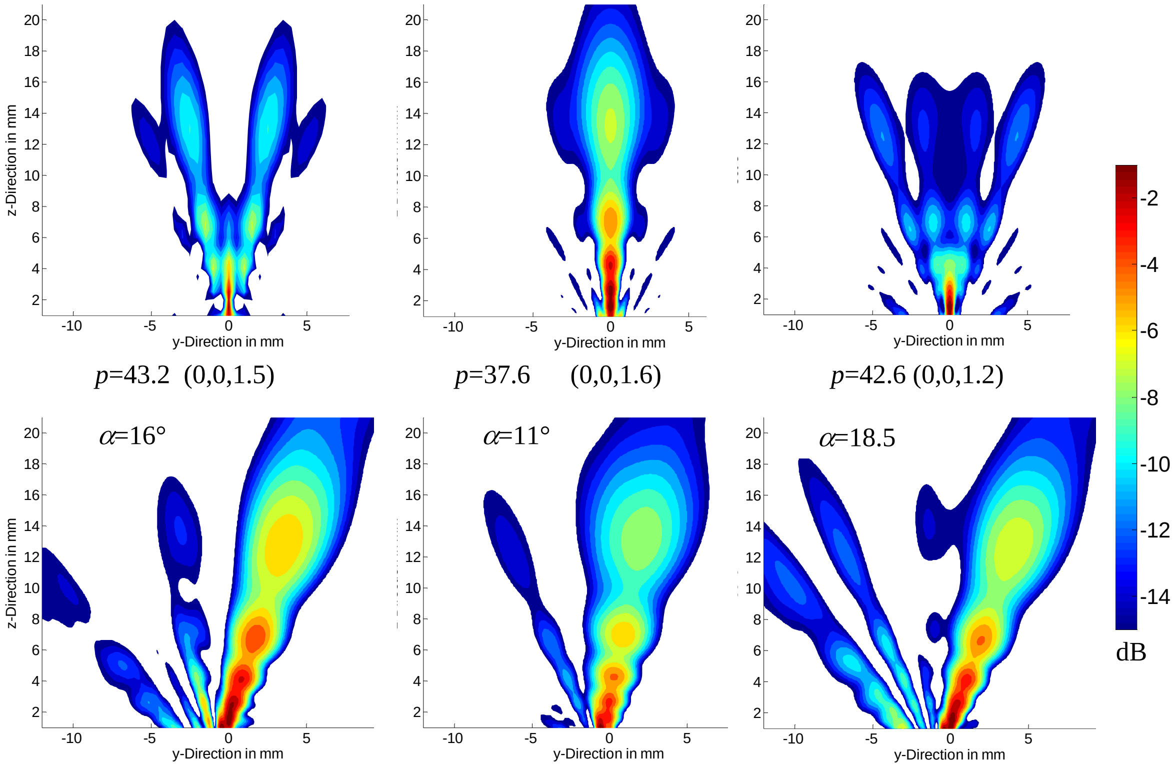
Figure 4. Time harmonic sound fields of a curved array (8 elements, frequency *f*= 10 MHz) in water for different focusing modes top: whole array, bottom: left semi array (first 4 elements)

5. Improvement of Sound Fields

Fig.5 deals with the improvement of the sound field by altering delay times. This is done for controlling F15, because in this case the largest side lobes exist in the sound field of the semi array (Fig.2a). For Fig.2 to 4, the delay times are determined geometrically considered an element as point in its center. In Fig.15a, the delay times are chosen in the same way but the ray is attached on the outer edge of the element. This new controlling is called controlling CE. For the semi array, this results in a larger steering angle than controlling F15 and the side lobe behind the main structure disappears. This means for the whole array: a little stronger focusing than controlling F15. However, this is not a real improvement since secondary off-axis structures nevertheless exist in a distance of about z=6mm, behind the focus.

An other possibility to correct the steering is a variation of the delay times of not all but of selected elements. The side lobe behind the main structure seems to be caused by an incorrect steering angle of the left and right edge elements. By switching off the edge elements in simulation of F15, the side lobe disappears; the main beam of the semi array has a smaller incidence angle and becomes more divergent. The maximum of the whole array is on the same location but it has a smaller amplitude (Fig.5b). That means that the sound field of less elements has a more extended sensitivity zone and the improvement therefore is still limited.

A better result is reached by another solution, whereby the inner elements are controlled by F15 while the edges are delayed stronger than in F15. An increased steering angle of the peripheral elements produces the sound field in Fig 5c. This offers a real improvement with diminished secondary structures, a stronger focusing, a small sensitivity zone and thereby a good resolution on this location.



a) Compensation of the array curvature with respect to element edge - controlling CE

b) Reduction to 6 elements for controlling F15

c) Controlling F15* with enlarged delay for peripheral elements

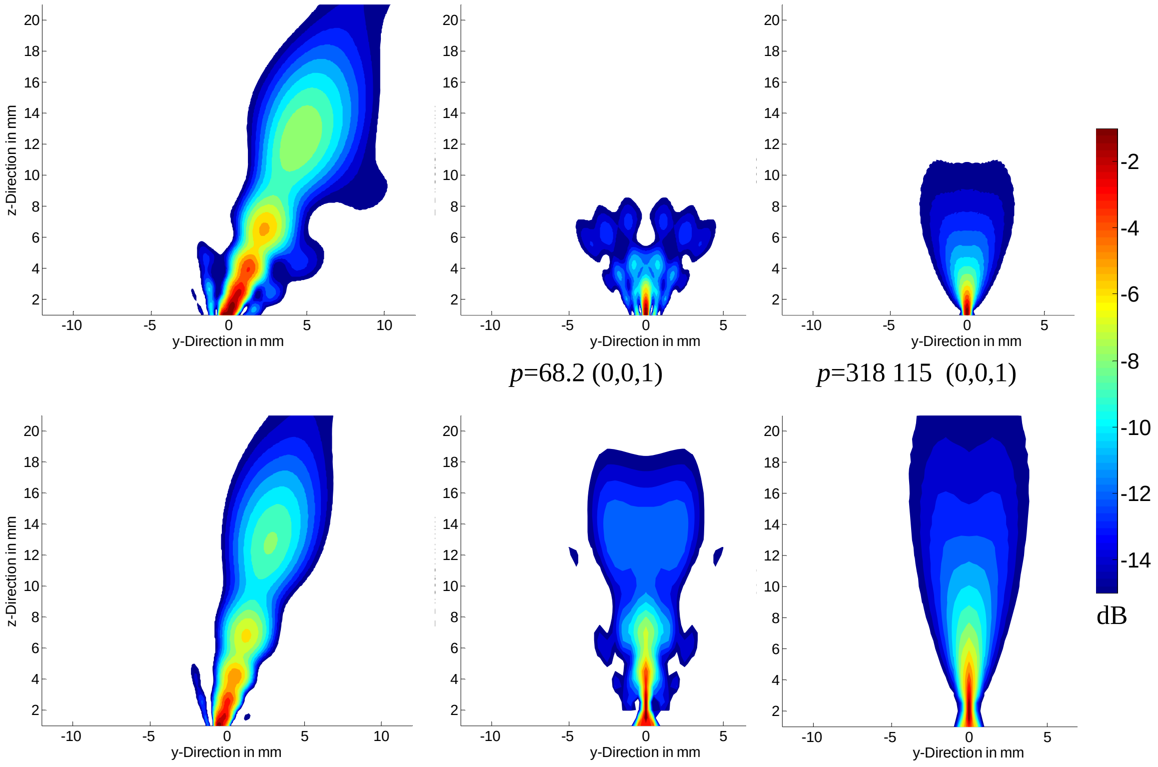
Figure 5. Improvement of sound field

Of course, the best improvement would be reached with element distances of $\lambda/2$ regarding to water. Fig.6 shows the calculated sound fields in the pipe wall for a 32-element curved array (the elements are four times closer to each other). The technical realization of such an array would be difficult because, instead of the original 68 elements around the cylinder, 272 elements have to be placed. Not to speak about all the electronics inside the cylinder. However, the calculation of the 32-element array field is applied to determine the energy loss by side lobes (incorrectness 1, 2 and 4).

Tab.1 compares sound fields of the 8-element and the 32-element array for different controlling modes at different center frequencies. The maximum of the 32-element array is always higher than that of the 8-element array. For the 32-element array, the element width of $\lambda/2$ regarding to water causes an improvement of controlling because

- there are no grating lobes in water and more energy is thus transmitted into the pipe wall,
- the splitting of the element into 4 parts and the steering of each part separately yields to a more exact focusing and better compensation of array curvature,
- applying the same delay times, the steering angle of outer elements becomes higher and they cross the focus.

The 32-element array realizes an increased maximum up to about 160% (line 1) for controlling F15 at a frequency of 10MHz. For a frequency of 5MHz, the maximum increases to about 130%. In this case, the element width of the 8-element array is λ with respect to water. Thus, the focusing is more exact and the energy loss caused by side lobes in water is smaller.



p=68.2 (0,0,1) *p*=318 115 (0,0,1)

p=68.9 (0,0,1.5) *p*=272.9 (0,0,2)

Figure 6. Sound fields of 32-element array (*f*= 10 MHz) in pipe wall for focusing modes F15 and C
top: Controlling F15, bottom: Compensation of array curvature C
left: semi array, harmonic middle: whole array, harmonic right: transient, 2 periods

Both the relation of the magnitudes of the maxima and the location of the maxima is well predicted by the comparison of time harmonic sound fields of the 32- and the 8-element array at corresponding center frequency.

Table 1. Comparison of maxima

		8 elements	32 elements	*p*1/*p*2
F15 at 10MHz	harmonic	*p*=42.8 (0,0,1.6)	*p*=68.4 (0,0,0.9)	0.62
transient	1 period	*p*=177.7 (0,0,1.5)	*p*=294.2 (0,0,1.0)	0.60
	2 periods	*p*=187.0 (0,0,1.5)	*p*=318.1 (0,0,1.0)	0.59
	5 periods	*p*=176.0 (0,0,1.4)	*p*=308.6 (0,0,1.0)	0.57
Compensation at 10MHz	harmonic	*p*=45.3 (0,0,2.6)	*p*=70.1 (0,0,1.7)	0.65
transient	1 period	*p*=167.9 (0,0,2.4)	*p*=256.8 (0,0,1.8)	0.65
	2 periods	*p*=179.3 (0,0,2.3)	*p*=276.9 (0,0,1.8)	0.65
	5 periods	*p*=172.7 (0,0,2.3)	*p*=267.5 (0,0,1.8)	0.65
F15 at 5MHz	harmonic	*p*=97.0 (0,0,1.8)	*p*=127.8 (0,0,1.0)	0.76
transient	1 period	*p*=327.6 (0,0,1.1)	*p*=440.4 (0,0,0.8)	0.74
	2 periods	*p*=353.5 (0,0,1.0)	*p*=467.9 (0,0,0.8)	0.76
	5 periods	*p*=343.5 (0,0,1.1)	*p*=454.2 (0,0,0.8)	0.76

6. Conclusion

- Caused by the finite elements (elements are no point sources), the real sound field of a convex array deviates extremely from the expected field according to the geometrically determined controlling mode. There is already a large difference between controlling with respect to the middle of the element and the element edge. Sound field calculations only inform about the effectiveness of controlling.
- An improvement of controlling is often reached by a stronger steering of the peripheral elements.
- Although the $\lambda/2$-condition is kept with respect to steel, steering and focusing take place in water. Therefore the keeping of the $\lambda/2$-condition with respect to steel is not the best available approach. After a water delay, smaller elements also yield to a better controlling result in steel.

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