UNDERWATER ACOUSTIC RADIATION OF PLANE SURFACES WITH AN ACTIVE COATING

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1 INTRODUCTION

Sources for underwater sound with large dimensions can be suitable for generating low-frequency sound. Possible applications are for example long-range communication, sonar and navigation. Dedicated underwater sound sources usually have a geometry designed for the acoustic application. Particularly with the large dimensions they require for the generation and control of low-frequency underwater sound with wavelength $\lambda > 1$ m, these sources are often difficult to integrate, especially in platforms of small design (e.g. autonomous underwater vehicles) and/or with special geometry (fast watercraft, submarines). In contrast, a sound source that can be generically attached to the existing geometry (e.g. a hull of a ship), such as an active coating, makes optimum use of the available surface area. Due to the adaptation to the existing geometry, it is not optimized for its acoustic application. Though, by a coating-like source design a significantly larger surface area with minimal impact on the geometry of the carrier platform can be used compared to dedicated sound sources. In this study, a thin active coating with actuators of thickness t and Radius R is investigated, for which the Helmholtz-numbers $kR < 1$ and $kt < 0.1$ apply. The properties of the coating as an underwater transducer are analyzed by creating a mathematical model and by conducting an experiment with regard to acoustic radiation and beam steering. The experiment is carried out for frequencies fitting to the sample-size of the coating and takes place with the active coating applied to a plane plate of Glassfibre Reinforced Plastic (GRP) under nearly acoustic free-field conditions in water.

2 COATING-LIKE SOURCES FOR UNDERWATER SOUND

A good overview of research work on active coatings or low-frequency underwater sound sources is provided by Pyun et al.[1]. They characterize and categorize the recent research work on this topic and show, that there are very few studies on transducer arrays, and among them only one deals with arrays of more than 10 elements (Mudiyala et al.[2]). In addition, a few studies should be mentioned here that are exemplary for research work in these areas and their applications mainly in the field of sonar or acoustic cloaking. For example, Howarth et al. investigate a coating for use in an underwater active acoustic attenuation control system[3]. The active part of the coating consists of a piezocomposite material (PCM), cast in an impedance matching layer for use under water. The published experimental investigations were carried out for the 1-D case in a pulse tube for a frequency of 5.4 kHz. Corsaro et al. investigate a tile-like design for a similar application, also with a PCM-actuator[4]. The active layer is thin at $t = 8\,\mathrm{mm}$ and is investigated for a frequency range between 0.4 and 5 kHz in a 1-D experiment.

With underwater communication as an application, Martins et al. present a transducer based on a PVDF-film[5] investigated in the broadband frequency range of 10 to 900 kHz. Due to the working principle of PVDF-films, an active coating with PVDF is only effective on curved surfaces or in a curved structure. Developments by Gentry et al.[6] and Tang et al.[7] in the field of SmartFoams, among others, make use of this fact, in which the PVDF-film is inserted into a foam in a curved form, here with the application case of active/passive underwater noise control.

However, the investigation of the presented work was carried out either in a 1-D experiment, e.g. pulse tube (Howarth et al., Corsaro et al., Tang et al.) or in a 2-D/3-D experiment but with only one actuator and not an array of several actuators resembling an active coating (Gentry et al., Martins et al.). In particular, studies on the beam steering behavior of larger arrays of thin actuators are not included in either the studies mentioned above or those listed in Pyun et al.

In this study, a thin coating in form of a transducer array of 18 elements is investigated in a 2-D wavefield underwater experiment for $kR < 1$ resp. $6 < ka < 9$ (with a the characteristic length of the array). The focus here is on directivity of sound radiation and on beam steering.

3 ANALYTICAL INVESTIGATION OF RADIATION AND BEAM

To model the radiation characteristics of the coating with an 3 x 6 (rows x columns) element array of actuators with radius R, that will be used in the experiment, first of all the radiation characteristics of the actuators have to be determined. The parameters of the array, used both in the model and in the experiment, are shown in Table 2.

Because of their geometry and with $0.42 \leq kR \leq 0.63$ applying to the selected frequencies for the experiment, the deviation between modeling as a point source and as a piston transducer must be considered.

Equation 1 expresses the sound pressure of an array of point sources, Equation 2 that of piston transducers[8]:

$$\underline{p}_{array}(r) = \frac{j\omega ck}{4\pi} \sum_i q_0 e^{-jkr_i} \tag{1}$$

$$\underline{p}_{array}(r,\theta) = j\omega ck \sum_i v_0 R^2 \frac{e^{-jkr_i}}{r_i} \frac{J_1(kRsin\theta_i)}{kRsin\theta_i} \tag{2}$$

Hereby is $\omega = 2\pi f$ the angular frequency, v_0 the velocity of the transducer surface corresponding to the sound particle velocity and r the distance between observation point and transducer. J_1 is the first order Bessel function, Θ the angle between the normal of the transducer and the observation point, and $q_0 = 4\pi R^2 v_0$ the source strength of the point source. The assumption for modeling the active coating as an array of point or piston transducers is, that the plate is rigid, there are no vibroacoustic effects and the sound is mainly radiated to the front side ($\Theta < \pm 90°$).

In Figure 1 the far field directivity factors $DF(\Theta) = \frac{p(\Theta)}{p_{max}}$ of a point source and a piston transducer

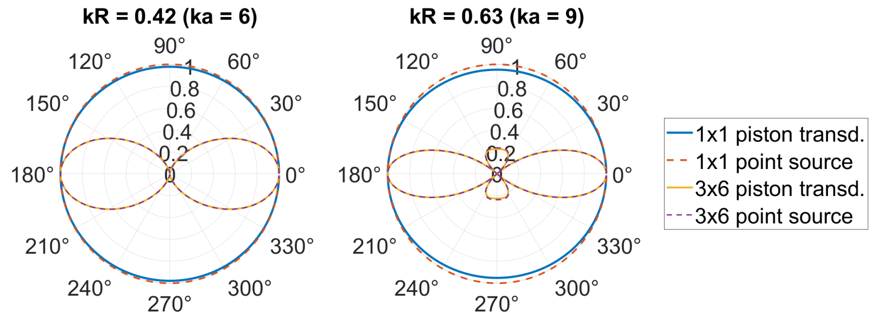


Figure 1: Directivity factor (far-field) for piston transducer vs. point source for different array sizes

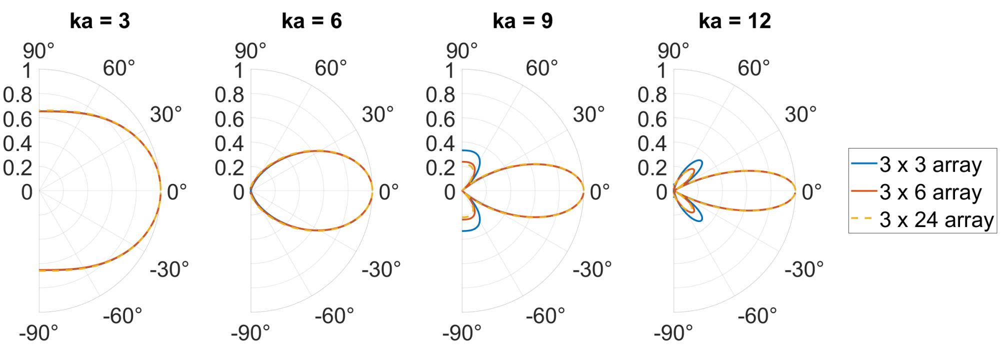


Figure 2: DF of different array sizes and different Helmholtz-numbers kR

model for the actuators of the array are compared. While there is a slight difference between the single point source and the single piston transducer, also increasing with kR, there is no remarkable difference between a 3 x 6 array of piston transducers and a 3 x 6 array of point sources ($6 < ka < 9$). Although it is not $kR << 1$, the difference between modeling the actuators as point sources and as piston transducers is very low, hence the beam is nearly a perfect circle displayed in polar coordinates. Based on these results, the actuators of the array are modelled as point sources for the subsequent investigations.

As only the array and no longer the individual actuator is considered in the following, the Helmholtz-number ka with the array length a is used for all further considerations. Figure 2 shows the directivity factor and especially the beamwidth for different array sizes and different values of ka. It is obviously, that for the same ka the directivity of the arrays is nearly the same. Remarkable is the different behavior regarding side lobes for arrays with the same ka. The difference here is the ratio between k and a, which is for $ka = 12$ as following for the arrays: $\frac{k}{a_{3x3}} = 396.4$, $\frac{k}{a_{3x6}} = 92.6$, $\frac{k}{a_{3x24}} = 5.5$.

For $ka \approx 6$, as investigated in the experiment, the $3\,\mathrm{dB}$-beamwidth ($BW_{3\,\mathrm{dB}}$) is approximately $43°$ for a 3 x 6 Array.

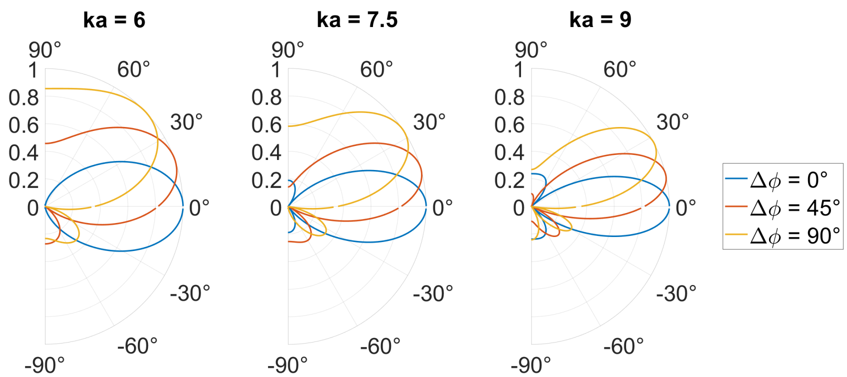


Figure 3: Beam steering - directivity factor of 3x6 array for different phase-differences $\Delta\phi$

Table 1: Resulting Θ ***for different ka and*** $\Delta\phi = 90°$

ka	$\Theta_{\Delta\phi=90°}$
6	$43.9°$
7.5	$37.6°$
9	$32.6°$

3.1 Beam steering

To calculate the beam steering performance of the array, the sound pressure $\underline{p}(r, \Delta\phi_i)$ produced by each actuator with the individual phase shift $\Delta\phi_i$ is summed up. In the experiment, the actuators are put together to three groups of 3 x 2 actuators. The actuators in each group will be driven by a signal with the same phase shift. As a result, there are three arrays of 3 x 2 actuators with phase shifted signals. The resulting pressure will be:

$$\underline{p}(r, \Delta\phi_i) = \frac{j\omega c k}{4\pi} \sum_i q_0 e^{-jkr_i + \Delta\phi_i} \tag{3}$$

As shown in Figure 3 there are two effects, that influence the beam steering behavior: With increasing ka the beamwidth decreases on one hand, and on the other hand the angle Θ by which the beam is shifted from its original direction, decreases due to

$$\Theta = arctan \frac{\Delta\phi}{k(2R + d)} \tag{4}$$

Hereby, d is the spacing between two actuators ($d < \frac{2}{1}R$), thus $2R + d$ is the distance between the center of two phase-shifted sources. For the beam steering shown in Fig. 3 the results shown in Table 1 apply for the far-field directivity.

4 ACTIVE COATING ON PLANE SURFACE

The active coating which is used here consists of piezoceramic actuators, 3D-printed spacers and a potting compound. The basic structure, to which the coating is attached, is a GRP-plate for maritime applications. The actuators are thin 33-type piezoceramics (diameter D to thickness t ratio $\frac{D}{t} \geq \frac{100}{6}$) and the potting compound AptFlex F22 by precision acoustics is a two-part, high-performance encapsulation

Table 2: Parameters used for the analytical model and for the experiment

Parameter	Value
actuator radius R	$25\,\mathrm{mm}$
actuator thickness t	$3\,\mathrm{mm}$
spacing between actuators d	$12\,\mathrm{mm}$
array rows n_z	3
array columns n_x	6
overall thickness of coating	$7\,\mathrm{mm}$

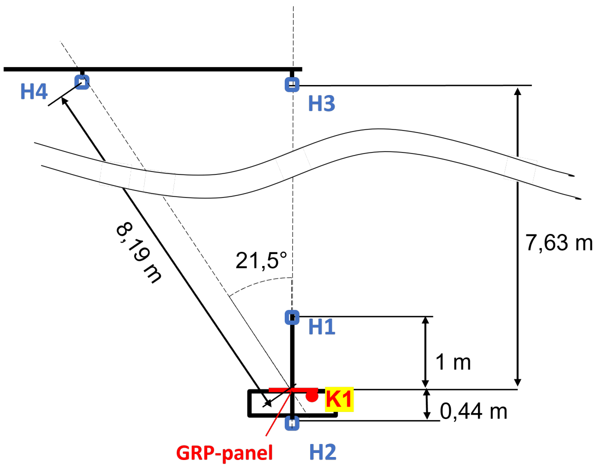
material with acoustic wave speed c similar to water ($c = 1500\frac{m}{s}$) that forms an impedance matching layer. Due to this composition the coating is comparable to a 1-3 piezocomposite known from literature[8 9], with two differences: First the actuators can better be characterized as disks than as rods, since it is $D >> t$, second in this experimental setup each actuator is separately connected and can be individually controlled. The GRP-plate used in the experiments in this study is a multi-layer sandwich construction with a rubber-coating for passive vibration damping applied on the side opposite to the active coating. The special purpose of the active coating is to transduce underwater sound of low frequencies, meaning $kR < 1$. So the single actuators are small and very thin compared to the wavelength of the sound they are supposed to emit ($kt < 0.1$). The properties of the coating for the experimental setup used in this and a previous study[10] are shown in Table 2. The thickness of $3\,\mathrm{mm}$ in this setup was chosen to properly investigate the sound radiation, the interaction between actuators and the GRP-plate and the limits of the signal chain. It is possible to chose much thinner actuators with $t < 0.5\,\mathrm{mm}$. One example are 1-D experiments with this type of coating using actuators with $t = 0.2\,\mathrm{mm}$[11].

5 EXPERIMENT

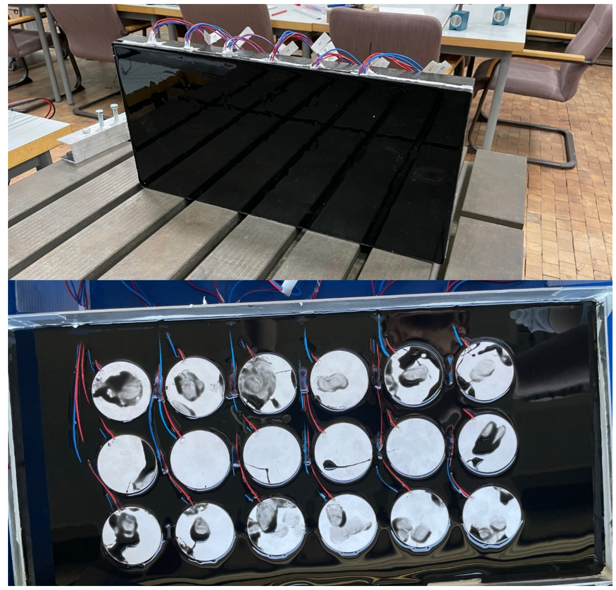
5.1 Experimental setup

The experiments on sound radiation and especially beam steering behavior of the array was conducted in the test facility of the Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) in Lake Plön in Germany. The test facility offers nearly acoustic free field conditions for underwater experiments, except for the reflections at the surface, and is ideal especially for low-frequency experiments. The GRP-panel was fixed in its test carrier and lowered to $4\,\mathrm{m}$ depth, surrounded by four Hydrophones (H1 - H4) in the same depth as shown in Figure 4a. Furthermore there is an accelerometer (K1) attached to the backside of the GRP-panel to observe the vibration of the plate.

The experiment was conducted for frequencies from $4\,\mathrm{kHz}$ to $6\,\mathrm{kHz}$ ($6 < ka < 9.1$). The frequencies in this range are low compared to the size of a single actuator. At the same time, they are high enough to ensure a sufficiently small beamwidth of the experimental array in order to be able to carry out a valid experiment on beam steering. The measurement was conducted with a sinesweep of $8\,\mathrm{Hz/s}$, that drives the actuators. The resulting sound pressure is recorded by the hydrophones H1 to H4 and is converted to the frequency domain by Fourier transformation. For beam steering, the three groups of 3 x 2 actuators are driven by the same, but by $\Delta\phi_i$ phaseshifted signal. $\Delta\phi$ is increased in steps of $15°$ from $0°$ to $90°$, a separate measurement is taken for each increment. The results shown in the diagrams in Figure 5b to 5h are interpolated between the measurements.



(a) Hydrophone-setup in Lake Plön (top view), all devices in 4 m depth



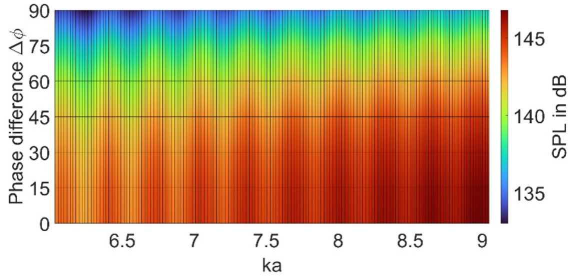
(b) GRP-plate with 3 x 6 piezoelectric actuators during (bottom) and after the potting compound is attached (top)

5.2 Results

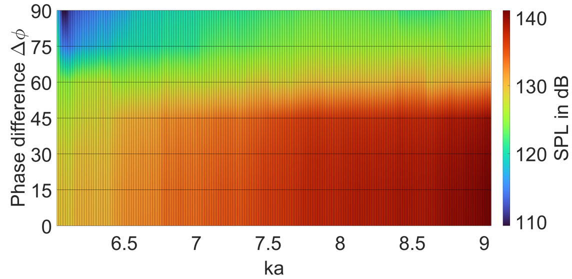
Figures 5a, 5c, 5e and 5g show the expected, interpolated results of the analytical model from section 3 for the following assumptions: rigid basic structure (GRP panel), ideal free field conditions, no attenuation loss. The surface reflections that occur at a depth of $4\,\mathrm{m}$ are modeled with image sources. There are some effects that were expected and are now shown by the analytical results: There is a difference in the sound pressure between observation points with different distances to the transducers due to geometric propagation. With changing $\Delta\phi$, the direction of the beam changes and it passes through the different observation points. The absolute sound pressure level increases with increasing kR. Except for the absolute level, the course of the sound pressure level does not change qualitatively for two observation points in the far field with different distances but in the same direction from the source.

Looking at the results shown in Figures 5b, 5d, 5f and 5h the following aspects stand out: At hydrophone H1 at a distance of $1\,\mathrm{m}$, there is a relatively sharp limit of the beam with $10\,\mathrm{dB}/15°\Delta\phi$, which can be recognized by the falling sound pressure level at $\Delta\phi = 60$°. Interference effects can be seen with hydrophones H3 and H4 in $r_{H3} = 7.63\,\mathrm{m}$ resp. $r_{H4} = 8.19\,\mathrm{m}$ distance. These interference effects can be traced back geometrically to the reflections on the water surface and therefore occur every $\Delta ka = 0.66$.

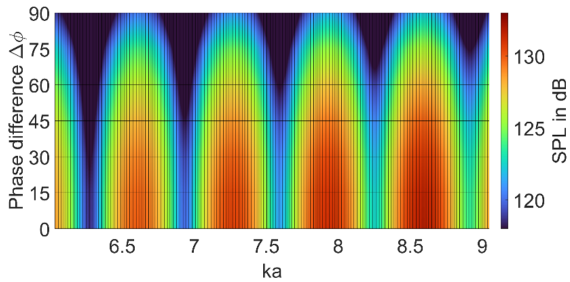
The progression of the sound pressure level at H3 ($r = 7.63\,\mathrm{m}$, $\Theta = 0°$) and H4 ($r = 8.19\,\mathrm{m}$, $\Theta = 21.5°$) shows how the beam passes through both hydrophones depending on $\Delta\phi$. While the beam is centered for $\Delta\phi = 0$, i.e. with the maximum on hydrophone H3, H4 is rather at the edge of the beam. Both in the measurements and in the modeling, the sound pressure level clearly shows how the beam shifts with increasing $\Delta\phi$. However, it is noticeable that for both hydrophones, although there is an angular shift $\Delta\Theta = 21.5°$ between them, there is the same sharp drop in the sound pressure level by $10\,\mathrm{dB}/15°\Delta\phi$ for $\Delta\phi > 60°$ as measured at H1. Because the effect is recognizable at each hydrophone and even at accelerometer K1, this can only be explained by interference and vibroacoustic effects. This can be compared to acoustic short circuit due to a large $\Delta\phi$ between the actuator groups, particularly between



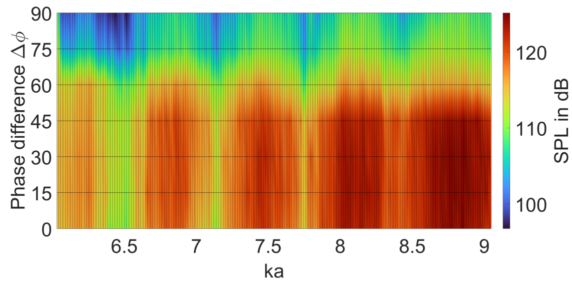
(a) SPL at 1 m distance, $\Theta = 0°$



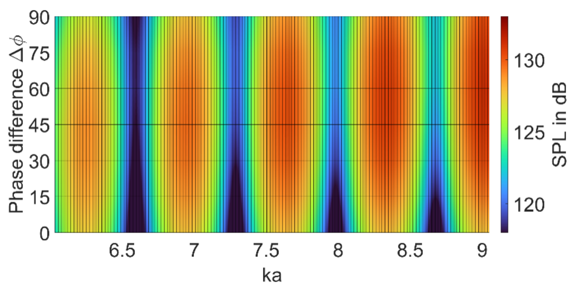
(b) SPL at 1 m distance, $\Theta = 0°$ ***(H1)***



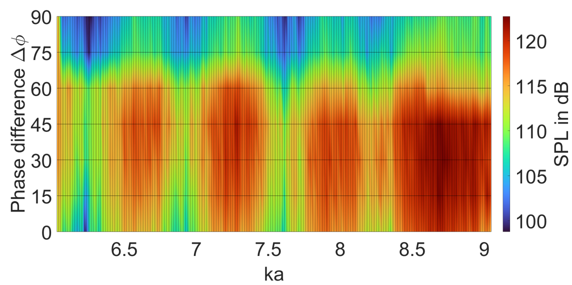
(c) SPL at 7.63 m distance, $\Theta = 0°$



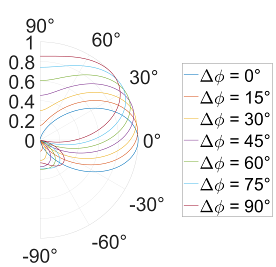
(d) SPL at 7.63 m distance, $\Theta = 0°$ ***(H3)***



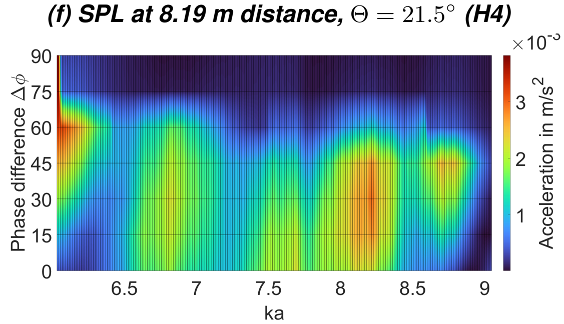
(e) SPL at 8.19 m distance, $\Theta = 21.5°$



(f) SPL at 8.19 m distance, $\Theta = 21.5°$ ***(H4)***



(g) Change of beam-direction for $ka = 6$



(h) measured acceleration of the backside of the GRP-panel (accelerometer K1)

Figure 5: Beam steering behavior - comparison of analytical (left) and experimental results (right)

actuator group 1 ($0°$) and 3 ($> 120°$). This means, that in this configuration of basic structure and coating, beam steering is possible for $\Delta\phi \leq 60°$. Effects such as superposition of the sound pressure of the individual actuators with an impact on the directivity factor and beam steering are well represented by the model. However, attenuation effects and the influence of the non-rigid plate in reality are not sufficiently taken into account.

6 CONCLUSION

With the active coating on plane surfaces it is possible to radiate sound with small and thin actuators for $kR < 1$. Despite the influences of the experimental environment and the vibroacoustic effects of the GRP-panel, the acoustic radiation of the active coating to the frontside can be modeled by an array of point sources. Due to the possibility of covering large areas with the coating, it can then offer a sharp beam and capabilities of beam steering due to a large number of actuators used in the coating. Already 3 x 6 relatively small actuators ($kR \approx 0.5$) reduce the $3\,\mathrm{dB}$ beamwidth to $< 51°$. The experiment in nearly free field conditions show a limit for beam steering at $\Delta\phi = 60°$. The influence of the vibroacoustic behavior of the GRP-panel on sound radiation has to be further investigated.

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