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Quantitative characterization of high-intensity focused airborne ultrasonic fields

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ABSTRACT

High-intensity focused airborne ultrasonic fields are increasingly applied in various technical fields, for example, to generate haptic feedback during gesture interaction. The sound fields used pose special challenges for a quantitative sound field characterization. The high sound pressure levels in combination with the higher harmonics generated by nonlinear effects require both, a wide dynamic range and a wide bandwidth of the measuring chain. Furthermore, the small wavelengths and the focusing result in spatially strongly varying sound fields. In the present case, a 40 kHz carrier signal was focused on a focal point using a transducer array with 256 elements.

Different microphone types and analysis methods were investigated with respect to their suitability in measuring high-power airborne ultrasonic fields. Using the portal scanner of the PTB, a spatial characterization of the ultrasonic field was performed. The results for different microphones and measurement setups were compared and will be presented and discussed in this paper. Due to the nonlinear propagation of the sound wave, peak sound pressure levels of more than 160 dB were measured in the focal region. To evaluate the exposure of potential users the measured sound pressure levels in the focal region were compared with currently existing limit values.

Keywords: Ultrasound, Metrology, Airborne

1. INTRODUCTION

Ultrasonic fields have been used to generate local audio sources for many years (1). The general idea behind this so-called parametric acoustic array is based on nonlinear acoustic effects of sound wave interaction in air (2). An ultrasonic carrier signal is amplitude modulated by an audio signal. When nonlinear interaction of sound takes place, the modulated audio signal is demodulated in the air. In this way audio sources with very sharp directivity pattern can be realized. The generation of nonlinear effects requires high sound pressure levels of the ultrasonic carrier signal.

Recently, a comparable technology has been developed to create haptic feedback during gesture interaction (3,4). The basic idea behind this application is to generate a tactile feedback in free space by using an ultrasonic phased array to focus high-intensity sound waves on user’s hand. The mechanoreceptors within the skin are sensitive to frequencies below 1 kHz. Therefore, a common approach is to modulate the ultrasonic carrier frequency by a low frequency signal.

Both applications use the ability of ultrasound to concentrate acoustic energy for the creation of localized low frequency sound sources. For this purpose ultrasonic fields with high sound pressure levels are used. In order to assess the potential noise exposure of users of such systems, quantitative sound field measurements must be performed. This paper describes a first approach and discusses challenges of measuring high-intensity focused airborne ultrasonic fields.

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2. EXPERIMENTAL SETUP

2.1 Ultrasonic Array

High-intensity focused ultrasonic fields were created using the commercially available Ultrahaptics STRATOS^{TM} explore development kit. It consists of a 16 x 16 transducer array and a control board. The piezoelectric transducers (muRata MA40S4S) have a resonance frequency of 40 kHz. The provided software tools allow the generation of different pre-defined sound field distributions. The sound field of all measurements presented here was focused stationary on a single focal point at a distance of 20 cm centered above the array. With a normalized intensity parameter, defined by the control software, the sound intensity could be adjusted between the values 0 (no sound) and 1 (maximum acoustic power).

2.2 Measurement Microphones

Measurements for sound field characterization were carried out using different microphones at different laboratories in order to examine the influencing factors of microphone selection, measurement setup and the entire measuring chain on the results. The specifications of the microphones used by Robert Bosch GmbH and by Physikalisch-Technische Bundesanstalt (PTB) are given in Table 1.

Table 1 – Specifications of the microphones used

Microphone type	Microphone cartridge	Preamplifier	Frequency range (± 3 dB)	Dynamic range	Sensitivity	Institution
GRAS 46BE IEPE (prepolarized) free-field microphone	1/4" 40BE	1/4" 26CB	4 Hz – 100 kHz	35 dB(A) – 160 dB	4 mV/Pa	Robert Bosch
GRAS 46DD IEPE (prepolarized) pressure microphone	1/8" 40DD	1/4" 26CB	6.5 Hz – 140 kHz	52 dB(A) – 175 dB	0.62 mV/Pa	Robert Bosch
GRAS (externally polarized) pressure microphone	1/8" 40DP	1/4" 26AS	6.5 Hz – 140 kHz	52 dB(A) – 178 dB	1 mV/Pa	PTB

1/4" and 1/8" measurement microphones were used for appropriate spatial resolution when scanning the sound field and to keep the influence of the directivity of the microphone as low as possible (5). The 1/4" free-field microphone set has a higher sensitivity and a lower intrinsic noise than the 1/8" microphones. The free-field microphone is designed to determine the sound pressure as it was in the absence of the microphone. In contrast, the 1/8" microphones as pressure devices measure the actual sound pressure on the surface of the microphone´s diaphragm, including sound pressure disturbances induced by the microphone itself. Since in the present case measurements are made under free-field conditions, the measured values determined with the 1/8" pressure microphones must undergo a free-field correction. As advantages over the 1/4" microphone, the 1/8" microphones offer a higher dynamic range, a wider frequency range and, due to their smaller diameter, a better spatial resolution including a lower influence of the directivity. A disadvantage of the 1/8" microphones is the lower signal-to-noise ratio of the measurement.

2.3 Measuring Quantities

As characteristic values for the evaluation of the measurements, the acoustic properties given in Table 2 were used. These measuring quantities are generally used in literature for the evaluation of airborne ultrasound exposure on users.

Table 2 – Measuring quantities and guiding limits (5,6,7,8)

Symbol	Term	Guiding limit
$L_{\mathrm{Zeq,Terz}}$	Z-weighted energy-equivalent continuous sound pressure level in one-third octaves	110 dB
L_{Zpeak}	Z-weighted peak sound pressure level	140 dB

As a measure in a limited frequency band around the 40 kHz center frequency of the carrier signal the one-third octave level $L_{\mathrm{Zeq,40kHz}}$ was used, whereas the peak sound pressure level L_{Zpeak} was applied as a broadband measuring quantity covering the whole frequency range including also higher harmonics.

Several standards and regulations issued by various institutions and valid in different countries exist which recommend ultrasound exposure limits. The guiding limits given in Table 2 are considered as a general consensus in literature (5,6,7,8). These values are derived for workday exposure conditions and hold at workplaces. Some published standards have exposure time limits and others do not (6,7). Increased limit values for reduced time are based on the “equal energy hypothesis”, which is applied in the audible frequency range. It is not proven, if this hypothesis is also valid for ultrasound exposure. It is therefore recommended to adhere to the conservative standards that define guiding values independent of exposure duration (6).

3. FOCAL POINT MEASUREMENT RESULTS

For the measurement results presented in this section one of the microphones was placed in the focal point, respectively. The intensity parameter was varied between 0.1 and 1.0 and the focal pressure signal recorded. Due to the nonlinear propagation effects, higher harmonics occur in addition to the carrier frequency. Preliminary investigations had shown that at least the first harmonic of 80 kHz should be sufficiently captured by the bandwidth of the measuring chain. Therefore, the data acquisition was done at Robert Bosch GmbH using a sampling rate of 384 kHz (measurement module GIM 282, ZODIAC DATA SYSTEMS GmbH) and at PTB with a sampling rate of 192 kHz (Data Translation DT 9847).

In Figure 1 a comparison between the recorded pressure time signals at the geometrical focus for the two microphones GRAS 1/4" 46BE and GRAS 1/8" 46DD is given. The measurements were performed with attached microphone protection grids. No free-field correction was made for the results of the 1/8" microphone in that case.

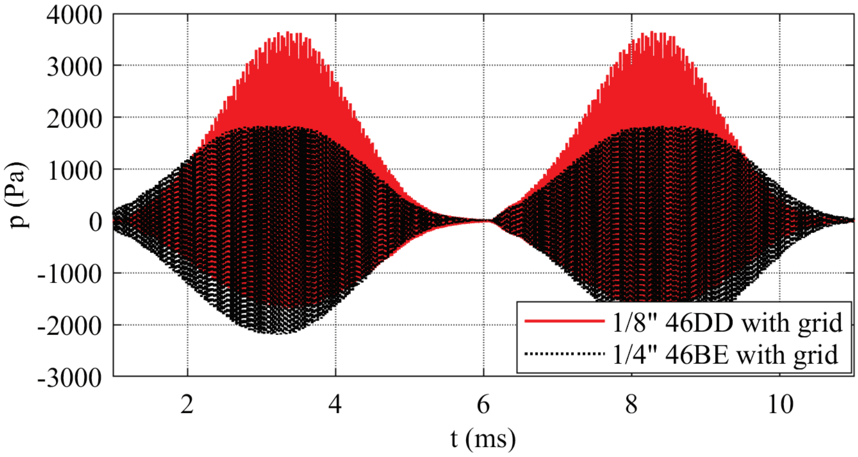

Figure 1 – Comparison of pressure-time signals for two different microphones (intensity setting = 0.8). Measurements done with microphone protection grid.

A 200 Hz amplitude modulation of the ultrasonic carrier signal can be seen. There are clear differences in the results of the two microphones both in terms of amplitude and signal shape. This is caused by the overestimation of the high frequency components due to the pressure microphone as well as by the influence of the microphone grid. Figure 2 shows for the same microphones the comparison of the measured one-third octave sound pressure level $L_{\mathrm{Zeq,40kHz}}$ with and without grid as a function of the intensity setting.

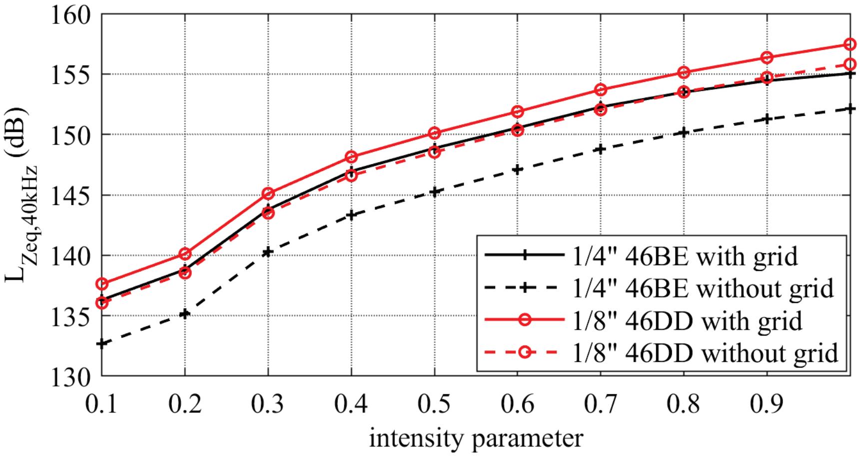

Figure 2 – Influence of the microphone protection grid on the measured one-third octave sound pressure level $L_{\mathrm{Zeq,40kHz}}$ as a function of the intensity setting. The grid leads to an overestimation of the measured values, where the effect on the 1/4" microphone is greater than on the 1/8" microphone. In this case no free-field correction for the pressure microphone has yet been taken into account.

The microphone protection grid leads to an overestimation of the measured pressure (9), independent of intensity. The effect varies in its impact for both microphones. In addition to the influence on the frequency response, the protection grid also has an influence on the microphone directivity at ultrasonic frequencies. For this reason, all further measurements were carried out without the grid.

Figures 3 and 4 compare the measurement results of the three microphones for the two acoustic parameters. The recorded raw signals were weighted with the respective transfer functions and the measurement data of the pressure microphones obtained a free-field correction. Overall, a very good agreement of the measurement results can be seen.

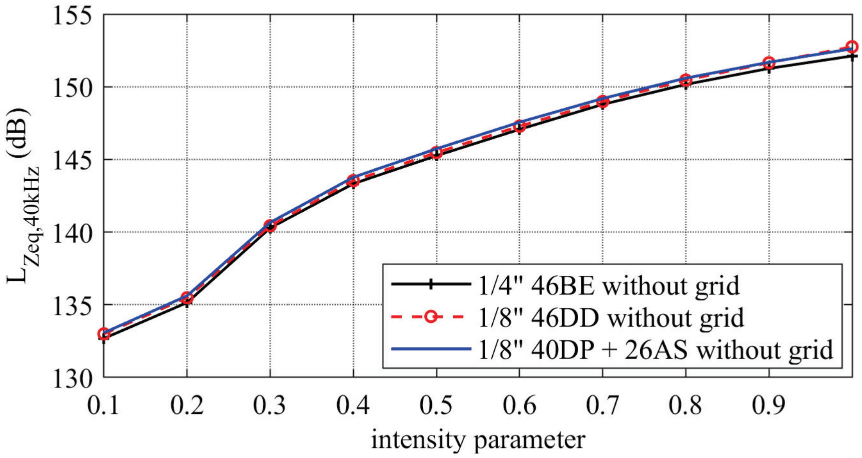

Figure 3 – One-third octave sound pressure level $L_{\mathrm{Zeq,40kHz}}$ measured at the focal point as a function of the intensity parameter setting. The results of the three different microphones show an excellent agreement with a maximum deviation of less than 0.6 dB. The measurements were carried out on different days and in different laboratories at Robert Bosch GmbH and PTB.

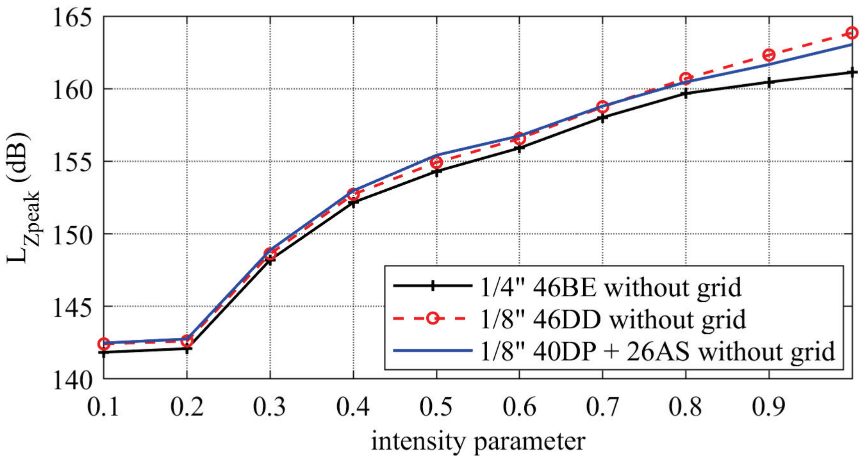

Figure 4 – Peak sound pressure level L_{Zpeak} measured at the focal point as a function of the intensity parameter setting. For intensity parameters up to 0.8, the results of the three microphones show very good agreement with a maximum deviation of about 1 dB. For the highest intensity range, larger deviations result because the dynamic limit of the 1/4" microphone was reached here. The measurements were carried out on different days and in different laboratories at Robert Bosch GmbH and PTB.

4. SPATIAL SOUND FIELD DISTRIBUTION

Besides measurements at the focal point, the spatial sound field distribution in areas in the vicinity of the focal point was also determined. For this purpose, the sound field was scanned in high resolution at different cutting planes. A computer-controlled 3D positioning system with three linear axes was used for automated scanning. The zero point of the coordinate system used corresponds to the center of the array surface. The focal point is located 200 mm above the center of the array ($(x, y, z) = (0,0,200)$) and thus, the array is located in the (x, y)-plane at z = 0.

Figure 5 depicts the sound field distribution measured in the (y, z)-plane and in the focal plane ($(x, y, 200)$-plane) at maximum intensity setting. The measurements were done with the 1/8" 40DP microphone using the PTB portal scanner. The spacing of the measuring points was 1 mm in a region of x, y = ±20 mm or y, z = ±20 mm around the geometrical focus and 5 mm outside. In propagation direction ((y, z)-plane) the focal volume has a conical shape with long extent. A sharp focus in lateral direction can be seen from the results in the focal plane. Besides the strong main lobe, pronounced side

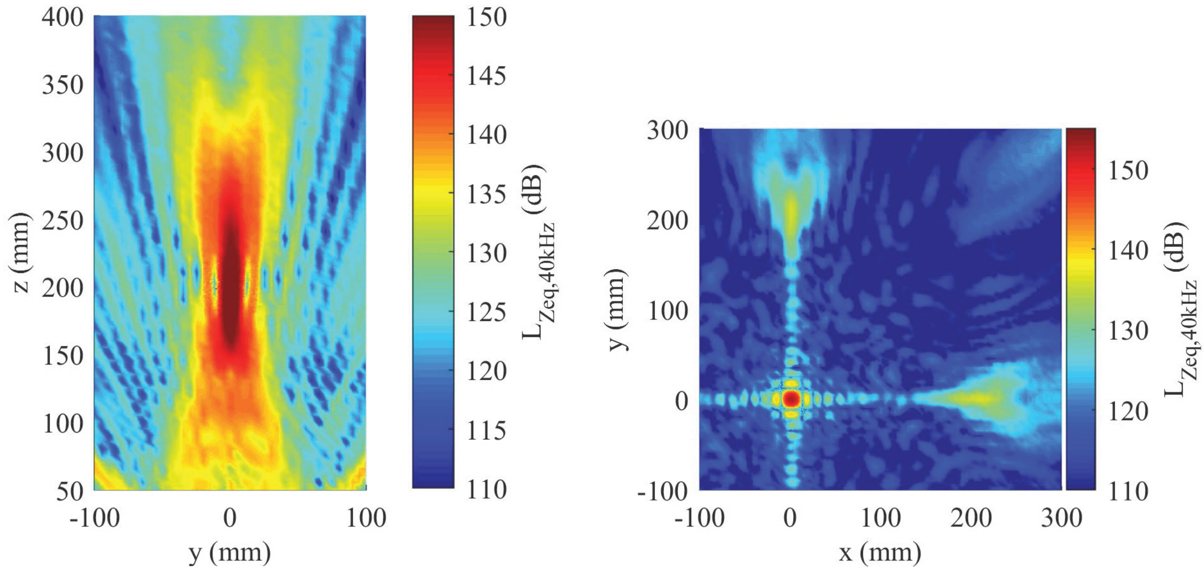

Figure 5 – Spatial distribution of one-third octave sound pressure level $L_{Zeq,40kHz}$ measured in (y, z)-plane (left) and (x, y)-plane at z = 200 mm (right) at maximum intensity setting. Measurements were done with 1/8" 40DP microphone using the portal scanner of the PTB.

lobes around the symmetry axes occur which are caused by the quadratic array arrangement. On the symmetry axes and in the (y, z)-plane the guideline limit for $L_{\mathrm{Zeq,40kHz}}$ is clearly exceeded in a large area. There are additional maxima with zones of high sound pressure levels clearly outside the array area. These grating lobes appear because the spacing between the array elements is greater than a wavelength. The diameter of the transducers is in the order of the wavelength, leading to a directive radiation pattern with a considerable part also in horizontal direction. Therefore due to the directivity pattern of the single elements and the array factor constructive interferences in undesired directions occur generating grating lobes with noticeable energy. The described effect also becomes clear in the illustration of the axial distribution in Figure 6. In addition to the narrow main lobe with a diameter (full width at half maximum) of about 14 mm grating lobes occur at a distance of approximately 200 mm away from the array center.

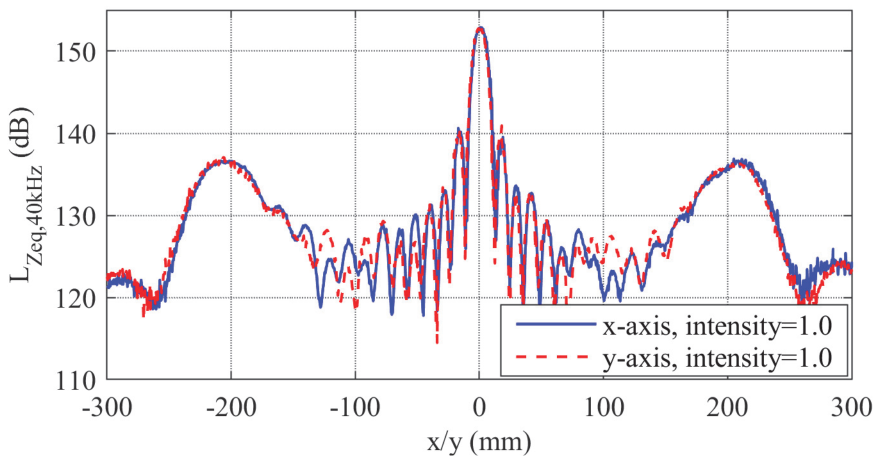

Figure 6 – Axial distribution of one-third octave sound pressure level $L_{\mathrm{Zeq,40kHz}}$ measured at z = 200 mm and maximum intensity setting. Measurements were done with 1/8" 40DP microphone using the portal scanner of the PTB.

The basic physical approach to generate a localized low frequency sound source by modulating a focused ultrasonic carrier signal becomes very clear from the results in Figure 7. Here the measured pressure signals in the focal plane $(x, y, 200)$ at maximum intensity setting are evaluated at different frequency bands. The measurements were performed at the Robert Bosch GmbH, using the 1/4" 46BE microphone and a 3D positioning unit. The spacing of the measuring points was 0.5 mm in a region of $x, y = \pm 20$ mm around the center and 1 mm outside. The frequency bands with the specified nominal center frequencies represent the 200 Hz modulation frequency, the 40 kHz carrier frequency and the harmonic component at 80 kHz. The results demonstrate the ability to generate a focused sound field with a low frequency component by modulating an ultrasonic carrier and use of nonlinear effects. The existence of higher harmonics is also the result of nonlinear effects. In a purely linear system, neither the modulation frequency nor a harmonic component would occur in the frequency spectrum of a modulated carrier signal. Compared to the spatial distribution at 40 kHz center frequency the maximum of the harmonic field component is about 12 dB lower.

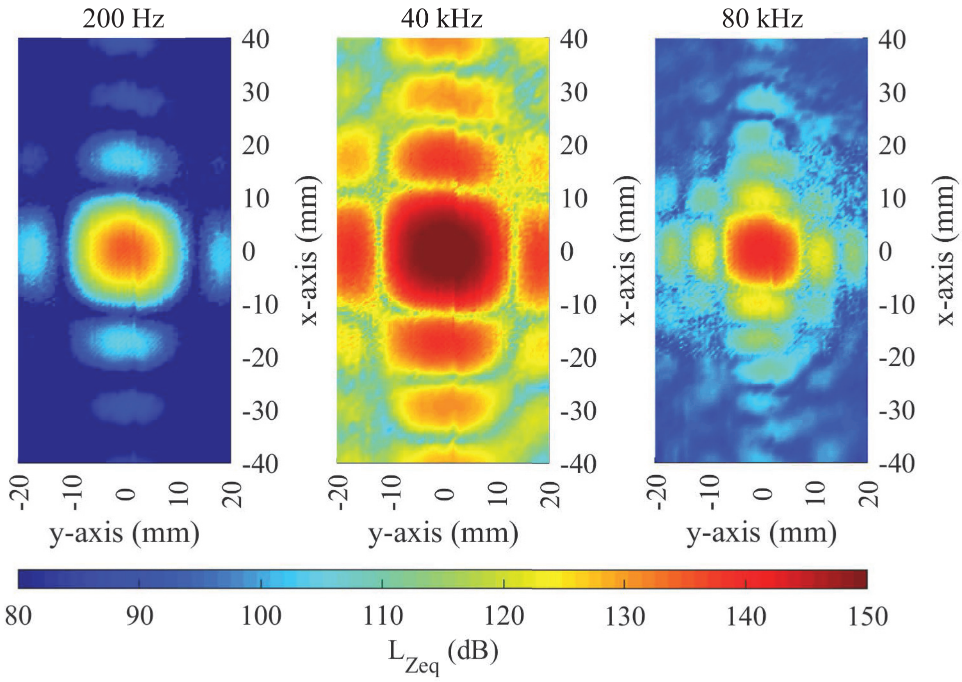

Figure 7 – Spatial distribution of one-third octave sound pressure level $L_{\mathrm{Zeq,Terz}}$ evaluated at the frequency bands with the specified nominal center frequencies according to the 200 Hz modulation frequency (left), the 40 kHz carrier frequency (middle) and the 80 kHz harmonics (right).

5. CONCLUSIONS

The strongly focused airborne ultrasound fields with very high sound pressures characterized in this study require a careful selection and use of suitable measurement microphones. When measuring without a protection grid and applying a free-field correction for pressure microphones, very good agreement between the measured sound pressure levels can be achieved with both 1/4" and 1/8" microphones. In terms of spatial resolution and when multiple harmonics need to be considered, 1/8" microphones are preferred.

With regard to user exposure the guiding limits are clearly exceeded in the focal region as well as far outside the geometrical focus due to the effect of grating lobes in the operation mode of a stationary single focal point considered in this study. The intended use of the investigated ultrasonic array is to create haptic feedback by projecting one or multiple focal points on user's hand. Further investigations under real use conditions including shielding effects by user's hand are necessary to evaluate the potential exposure of users to hazardous high ultrasound pressure values.

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