Investigation of spatial averaging effect of membrane hydrophones for working frequencies in the low MHz range

Olga Bessonova, Volker Wilkens

Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, E-Mail: olga.bessonova@ptb.de

1. Introduction

Acoustic fields produced by medical ultrasound equipment are most commonly characterized using piezoelectric hydrophones. Spot-poled membrane hydrophones employ the polymer polyvinylidene fluoride as the sensitive element with thicknesses from 9 µm to 30 µm. Effective diameters are in the range of 0.2 mm to 1 mm. In modern medical applications of ultrasound, such as high intensity therapeutic ultrasound (HITU), the ultrasound field is strongly focused and the size of the focal area is comparable with these latter values. Thus, the effective radius of the active element is an important characteristic of a hydrophone. When it is too large, significant averaging of the acoustic pressure over the active element occurs and leads to an underestimation of the measured peak pressure. Current standards provide constraints on the maximum effective radius to be used in a given ultrasound field [1, 2]. However, practical requirements of an adequate signal-to-noise ratio or other considerations can lead to the use of a hydrophone with an element size larger than the recommendation. In this case, a correction must be applied to compensate for the resultant spatial-averaging effect. A simple practical but rough correction method is described in reference [2].

The goal of this work was to understand the implications of the effective radius data of typical membrane hydrophones as derived from directional response measurements being strongly frequency dependent, in particular in the case of ultrasound frequencies in the low MHz range.

2. Experimental setup and numerical model

The actual averaging behavior was investigated by measuring the ultrasound field profiles with membrane hydrophones of different effective radii and by comparing them with the profiles simulated numerically. The source used in the experiments was a single element spherically focusing transducer with parameters typical for those used in HITU: source radius of 32 mm, focal length of 62.6 mm, and frequency of 1 MHz or 3 MHz. Due to the large aperture and short focal length, this transducer results in a strong focusing with a small lateral beam size at the focus. Together with the low operating frequencies, this poses extreme conditions for the membrane-type receiver. Three hydrophones with different sizes of the active elements were used to measure the acoustic pressure: RS072 (PTB, 0.1 mm), PTB42 (PTB, 0.25 mm), and B014 (Marconi, 0.5 mm).

Figure 1 shows the frequency dependence of the effective radius for the smallest hydrophone, RS072, used as derived from directional response measurements [3]. According to the IEC standards [1, 2], the effective radius used should not be larger than 0.38 mm at 1 MHz and 0.12 mm at 3 MHz, respectively. But even for this smallest available hydrophone, the effective radius is about two times larger than the recommended one. Only the effective radius derived at high frequencies (20 MHz and above) would be in line with the standards for measurements at frequencies below 3 MHz. So a first question was: Which effective radius is relevant in real beam profile measurement applications where the membrane is perpendicular to the beam axis? The enlarged value determined by directional response measurements under a strong influence of Lamb waves induced in the obliquely insonated membrane at the low source working frequency, or the one determined at the higher frequencies being closer to the geometrical electrode size of the receiving element frequently referred to as nominal size?

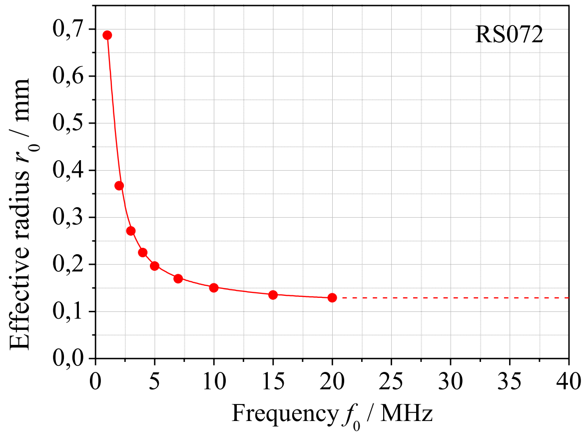

Figure 1: Frequency dependence of the effective radius of the hydrophone RS072.

In the accompanying numerical sound field simulations, the propagation of a focused axisymmetric acoustic wave in a nonlinear medium was governed by the Khokhlov-Zabolotskaya-Kuznetzov equation:

$$\frac{\partial}{\partial\tau}\left[\frac{\partial p}{\partial x}-\frac{\varepsilon}{c_0^3\rho_0}p\frac{\partial p}{\partial\tau}-\frac{c_0^3\rho_0 F}{b\omega_0^2}\frac{\partial^2 p}{\partial\tau^2}\right]=\frac{c_0}{2}\Delta_\perp p\ . \qquad (1)$$

Here p is the acoustic pressure, x is the propagation coordinate, τ is the retarded time, ε is the coefficient of nonlinearity, ρ_0 is the ambient density, c_0 is the speed of sound, F is the source focal length, ω_0 is the angular frequency, and b is the dissipative coefficient. The boundary condition was given at the circular focusing source as a harmonic wave with initially uniform amplitude distribution. The numerical time-domain algorithm used here to solve Eq. (1) has been described in detail in reference [4].

3. Results

Firstly, the acoustic pressure was measured (RS072) at the geometrical focus across the beam axis (Fig. 2). The results shown in the graph are normalized to the maximum value (blue points). The measurements shown here and later on were carried out at the frequency 3 MHz, as this condition turned out to be more illustrative to demonstrate the spatial averaging effect than for excitation at the frequency 1 MHz.

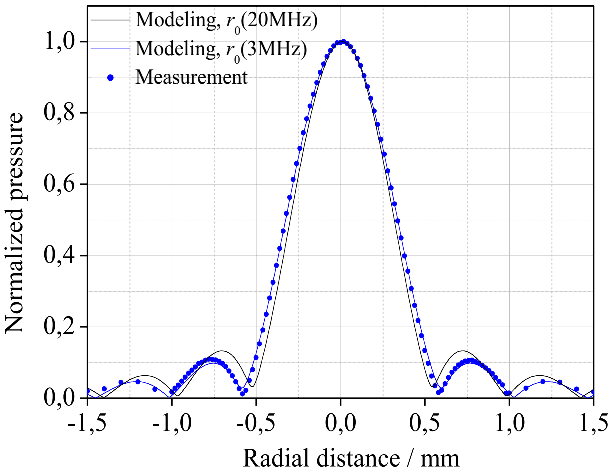

Figure 2: Measured (blue point) and modeled (black and blue lines) lateral beam profiles at the focus. Modeling results were averaged over circular areas corresponding to two different effective radii r_0 for comparison.

The amplitude at the source was very small ensuring linear propagation conditions. The results of the acoustic pressure modeling were averaged over a circular area with radius corresponding to the effective radius at 3 MHz ($r_0 = 0.27$ mm, blue line). In addition, averaging was performed for the effective radius at high frequencies ($r_0 = 0.13$ mm, black line). However, in Fig. 2 the best agreement of experimental and simulation results occurs for the enlarged effective radius at the low source working frequency.

Figure 3 shows the modeled peak compressional and rarefactional pressures at the focus as a function of the pressure at the source. By increasing the source amplitude, combined effects of nonlinearity and diffraction lead to the fact that peak compressional pressure is much higher than peak rarefactional pressure, i.e. nonlinear effects are significant. Numerical modeling was performed for three different cases: firstly, without spatial averaging (red line), that is why the calculated pressure is higher than measured; secondly, with spatial averaging according to the effective radius at the working frequency (black line). This provided significantly lower results for high source amplitudes than in the experiment. Finally, the effective radius at high frequencies was used for spatial averaging (blue line). This gave the best agreement in the case of nonlinear propagation, where the wave spectrum consists of the many harmonics.

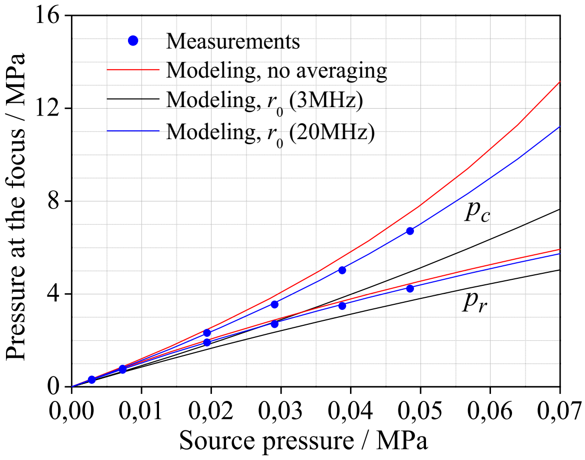

Figure 3: Dependence of peak compressional p_c and peak rarefactional p_r pressure at the focus on the source pressure.

The results of lateral beam profile measurements at the geometrical focus obtained using the three hydrophones of different element size show the impact of the effective radius on the measured peak pressure amplitude (figure 4). Although the measurement conditions were the same for all three cases, there are large differences in the obtained results. For comparison, the acoustic pressure field was also modeled without spatial averaging, corresponding to an "ideal point receiver" hydrophone (black line). As can be seen, even the smallest available hydrophone, RS072, underestimates the actual pressure by more than 20 %, and for the largest hydrophone, B014, the difference is already 75 %. An appropriate correction for such cases may be provided by individual sound field modeling.

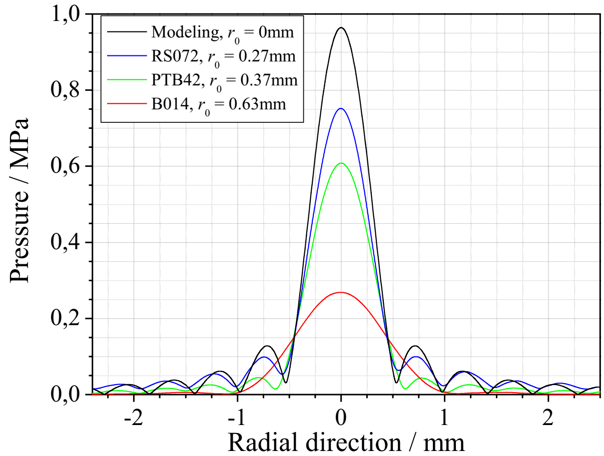

Figure 4: Wave profiles modeled and measured with three different hydrophones at the focus across the beam axis.

4. Conclusions

The field of the HITU source was modeled and measured using hydrophones of different active element size. In general, the reduction of pressure data measured is more pronounced for large active elements and for high frequencies. Under low amplitudes at the source (linear propagation conditions), the membrane hydrophone radius relevant for spatial averaging corresponds to the enlarged effective radius obtained from directional response measurements at the low source working frequency. For higher source amplitudes (nonlinear propagation conditions), the wave spectrum consists of many harmonics. Therefore, the radius of a hydrophone relevant for spatial averaging corresponds to the effective radius determined at high frequencies.

Literature

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[2] International Electrotechnical Commission, International Standard, IEC 62127-1 (2007).

[3] Wilkens, V., Molkenstruck, W.: Broadband PVDF membrane hydrophone for comparisons of calibration methods up to 140 MHz. IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 54 (2007) 1784-1791

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