MEMBRANE HYDROPHONE WITH FLEXIBLE LATERAL RESOLUTION FOR ULTRASONIC FIELD CHARACTERIZATION

R. Reibold and W. Molkenstruck
Physikalisch-Technische Bundesanstalt, Braunschweig, GERMANY
rainer.reibold@ptb.de

Abstract

For the characterization of ultrasonic fields – particularly in high-frequency applications – sensors with high lateral resolution are required. Because of the finite size of their sensitive area, commercial piezoelectric hydrophones do not always comply with the requirements. In previous papers, the reconstruction of ultrasonic fields by unfolding the hydrophone aperture effects was investigated both theoretically and experimentally. The improvement of the lateral resolution by means of this technique is a convincing result but there is an essential disadvantage: Data evaluation by means of deconvolution requires the whole sectional plane of interest of the sound field being scanned. That means that data acquisition is time consuming and point by point measurement impossible.

In the paper a new membrane-type hydrophone is presented the sensitive area of which covers one quadrant. Under this condition, the sound pressure is folded with a two-dimensional step function when the ultrasonic field is scanned. The achievable lateral resolution simply depends on the sampling interval which can be adjusted to the sound field under test. The reconstructed sound field can easily be obtained using the method of finite differences.

Besides a drastical reduction of the required data storage capacity, the new concept enables quasi point by point measurements not only of continuous waves but also of broad-band pulses.

Introduction

In the past few years, various papers dealing with the improvement of the lateral resolution of hydrophones have been published reflecting three alternative developments. One of these is concentrated on the miniaturization of piezoelectric hydrophones [1,2] or on new sensors based on fibre-optical or interferometric techniques [3-5]. The second approach relates to methods for correcting the spatial averaging effect [6-9] using idealized models which are, however, restricted to particular regions of the sound field. The third approach finally deals with the deconvolution of the hydrophone aperture effects [10-11].

This paper deals with a new membrane-type hydrophone which is based on the promising experience gained with the deconvolution technique for finite-size hydrophones. It basically consists of a sensitive area formed by one quadrant and hence integrates the pressure over that part of its area overlapping with the sound field. This hydrophone type enables quasi point by point measurements, and this with a substantially reduced need for data storage.

Theory

A membrane hydrophone is considered one quadrant of which serves as sensing element. The hydrophone diameter is greater than twice that of the sound beam so that the sensing element is capable to covering its essential part (Fig. 1).

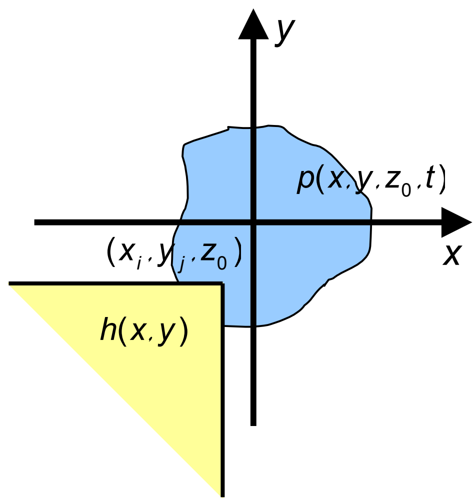

Fig. 1: Sketch of the sound pressure $p(x, y, z_0, t)$ and the hydrophone sensing element with impulse response $h(x, y)$.

It is further assumed that the hydrophone with the spatial impulse response $h(x, y)$ acts as a space- and time-invariant, linear receiving system and that it excels by a constant space-independent sensitivity. For a sound field represented by the pressure $p(x, y, z_0, t)$, where z_0 is the axial distance from the sound source, the hydrophone output voltage is then obtained by the two-dimensional convolution operation (see e.g.[12]):

$$v(x, y, z_0, t) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(\alpha, \beta, z_0, t) h(x-\alpha, y-\beta) \mathrm{d}\alpha \mathrm{d}\beta = p(x, y, z_0, t) ** h(x, y) \quad (1)$$

On the above-mentioned assumptions, $h(x,y)$ can be expressed as a two-dimensional step function and eq. (1) can then be written as:

$$\begin{aligned} v(x,y,z_0,t) &= p(x,y,z_0,t) ** C \cdot \mathrm{step}(x,y) \\ &= C \cdot p(x,y,z_0,t) * \mathrm{step}(x) * \mathrm{step}(y) \end{aligned}, \quad (2)$$

where C is a proportionality factor and the right-hand side of the equation allows for the separability of $\mathrm{step}(x,y)$.

In the experimental practice, the sound field is scanned using equal intervals in the x- and y-direction, the step width must be adequately chosen to fulfil the demands on spatial resolution. Reconstruction is performed in the space domain using the method of finite differences (see e.g. [13]). For a particular position (x_i, y_j, z_0), the hydrophone output voltage is given as:

$$\begin{aligned} \Delta^2_{x,y} v(x_i,y_j,z_0,t) &= v(x_i + \tfrac{1}{2}\Delta x, y_j + \tfrac{1}{2}\Delta y, z_0, t) \\ &- v(x_i - \tfrac{1}{2}\Delta x, y_j + \tfrac{1}{2}\Delta y, z_0, t) \\ &- v(x_i + \tfrac{1}{2}\Delta x, y_j - \tfrac{1}{2}\Delta y, z_0, t) \\ &+ v(x_i - \tfrac{1}{2}\Delta x, y_j - \tfrac{1}{2}\Delta y, z_0, t) \end{aligned} \quad (3)$$

and hence

$$\frac{\Delta^2_{x,y} v(x_i,y_j,z_0,t)}{\Delta x \Delta y} = C \cdot p(x_i,y_j,z_0,t)\,, \quad (4)$$

where Δx and Δy are the respective sample intervals. Eq. (4) reveals that four measurements are basically needed to determine the sound pressure in any position.

Experiments

The hydrophone used in the investigation was developed at the PTB and can by no means considered optimized. It consists of a PVDF foil 25 µm thick streched over a perspex ring with an inner diameter of 68 mm. The electrodes are sputtered with chromium about 200 nm thick and cover one quadrant of the membrane. Polarization is performed at room temperature using an electric field strength of 2 MV/cm of 5 min duration. A differential preamplifier (DC to 80 MHz) is incorporated in the perspex ring. No special electric shielding is provided.

The sound source is a focussing broad-band transducer (bandwidth 1.5 MHz to 2.5 MHz) 20 mm in diameter and with a focal length of 55 mm. The sound transmitting medium is degassed and deionized water.

For the experiments tone-burst operation was chosen to avoid cross-talk distortion by the transmitting transducer and thermal drift due to temperature changes in the sound transmitting medium. An essential part of the data acquisition system is the sampling oscilloscope (TEK TDS 3032B) with a vertical resolution of 9 bit which enables phase measurements in tone-burst operation relative to a cw reference signal. In order to achieve a resolution and a signal-to-noise ratio as high as possible, the data are averaged 512 times.

In Fig. 2 a plot of the amplitude data acquired in the focal plane of the transducer at 1.9 MHz is presented. It shows the typical shape which is mainly due to the increasing domain of integration. The highest voltage is obtained when the hydrophone's active area completely intersects the sound field.

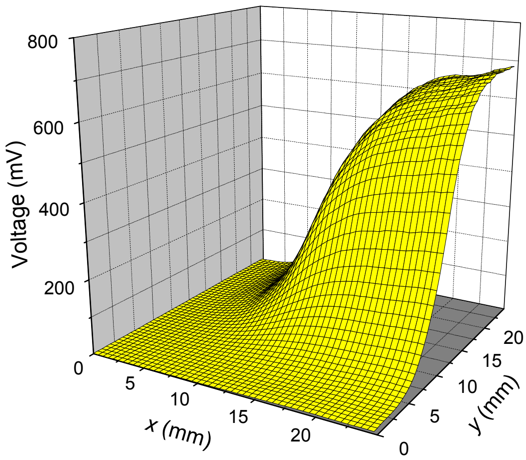

Fig. 2: Amplitude data acquired in the focal plane of the transducer. f=1.9 MHz; $\Delta x = \Delta y = 0.25$ mm.

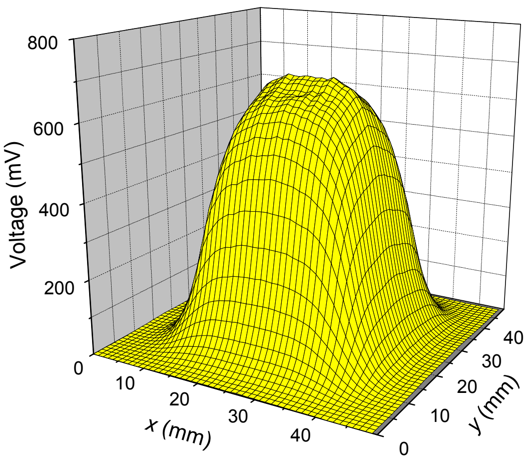

Fig. 3: Symmetrically completed set of measured values of Fig. 2 used for low-pass filtering.

The evaluation procedure represented by eq. (4) enhances noise and, hence, makes low-pass filtering indispensable. In order not to affect the measured values in an inadmissible manner (Fig. 2, drop at the rim), the data are repeated to form a symmetrical profile as shown in Fig. 3, and then are filtered.

Fig. 4 shows the pressure profile in the focal plane evaluated using the data of Fig. 2 together with that obtained using a needle-type hydrophone 0.8 mm in diameter as reference.

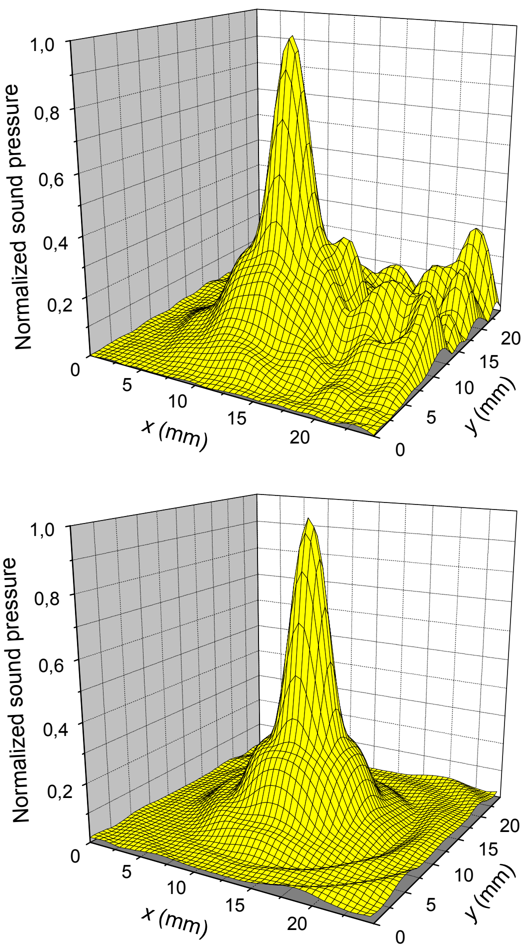

Fig. 4: Sound pressure profile in the focal plane (55 mm) of a circular sound source at 1.9 MHz. Top: Measured using the quadrant hydrophone and evaluated according to eq. (4). Bottom: Needle-type hydrophone as reference. Sample interval: 0.25 mm.

The left half of the profile obtained with the quadrant hydrophone is in good agreement with the reference measurement, whereas the right half reveals remarkable distortions due to reflections from the perspex ring.

In order to demonstrate the efficiency of the new hydrophone concept, time waveforms in the focal point of the sound source are also taken. As already mentioned above, four measurements in neighbouring positions are necessary (see eq. (3)) to determine the pressure waveform in a particular point. Fig. 5 shows the temporal variation of the voltage in the four positions using the quadrant hydrophone together with the time waveform of the pressure in an individual position evaluated according to eq. (4) and of the

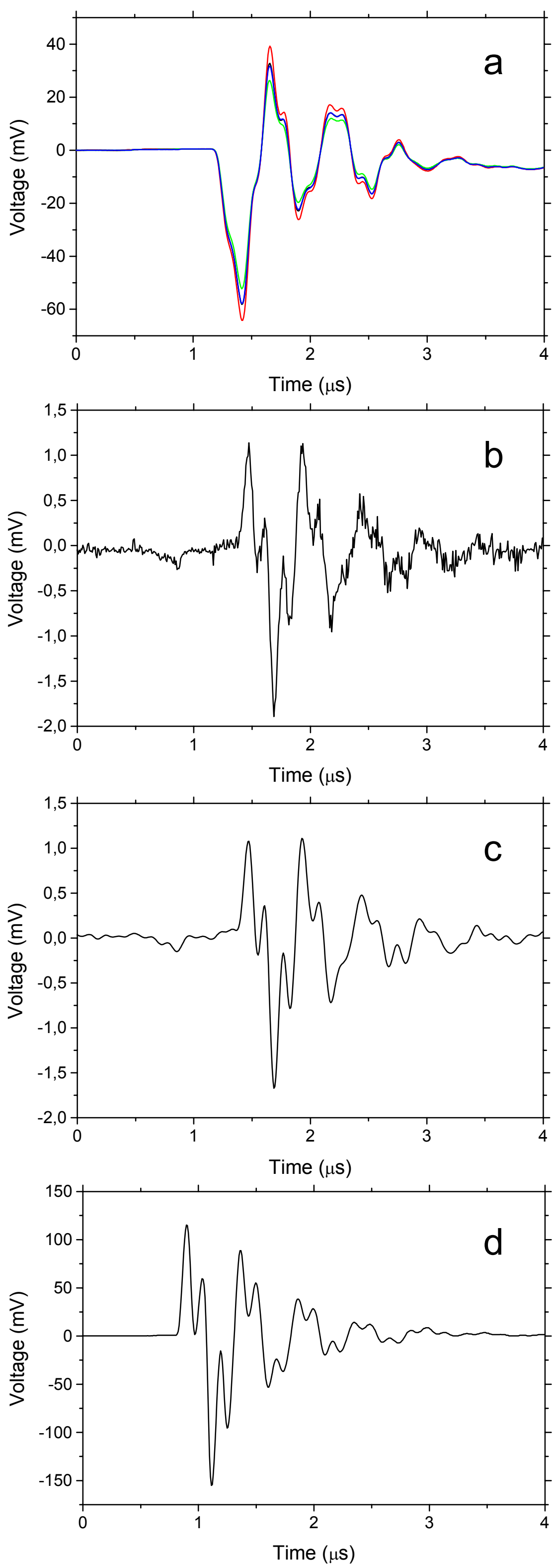

Fig. 5: Temporal variation of the voltage in four neighbouring positions using the quadrant hydrophone (a), in a particular position calculated according to eq. (3) (b), as in (b) after band-pass filtering (c). Time waveform of the reference signal (d).

reference signal. The spatial sampling interval is 0.5 mm. The time waveforms are recorded using an 8 ns interval. For the reference measurement, the needle-type hydrophone had to be exchanged for a membrane hydrophone (1 mm in diameter) since this type of hydrophone does not exhibit strong sensitivity variations in the frequency range considered.

Although optimized neither in view of amplitude resolution nor in view of time resolution (precision of the trigger signal), the time waveform of the quadrant hydrophone exhibits good agreement with the reference.

Discussion

A new membrane-type hydrophone has been presented the sensitive area of which consists of one quadrant. When scanning an ultrasonic field it integrates on two dimensions over the overlapping area covered by the sound field and the hydrophone's active area. The spatial sampling interval can be fitted to the demands on the spatial resolution of the sound field under test. Using a simple finite differences scheme the complex-valued sound pressure is evaluated. In contrast to finite-size hydrophones, this „infinite"-size hydrophone makes quasi point by point measurements possible.

For several reasons the preliminary experimental conditions can by no means be considered optimized:

- The hydrophone was designed at the PTB and its properties therefore are not comparable with those of instruments produced by specialized manufacturers.
- The sensitive area was too small to intersect a complete cross-sectional area of the sound field.
- The hydrophone was not electrically shielded so that the cross talk in the pulse operation could not be reduced to an appropriate level.

In spite of the limitations described, the agreement between the quadrant hydrophone results and those of the reference is acceptable. It can therefore be expected that hydrophones of specialized manufacturers, together with modern electronic equipment with high amplitude and time resolution and with an appropriate signal processing system, will provide a measurement technique for high-frequency ultrasonic field characterization.

References

[1] P. Lum, M. Greenstein, E.D. Verdonk, C. Grossman, and T.L. Szabo, „A 150-MHz-bandwidth membrane hydrophone for acoustic field characterization", Hewlett-Packard J., vol. 49, pp. 6-16, 1999.

[2] A. Selfridge and P. Goetz, „Ellipsoidal hydrophone with improved characteristics", IEEE Ultrason. Symp. 1999, pp. 1181-1184.

[3] P.C. Beard and T.N. Mills, „A miniature optical fibre ultrasonic hydrophone using a Fabry Perot polymer film interferometer", Electron. Lett., vol. 33, pp. 801-803, 1997.

[4] T.J. Esward and S.P. Robinson, „Extending the frequency range of the NPL primary standard laser interferometer for hydrophone calibration to 60 MHz", IEEE Trans. UFFC, vol. 46, pp. 737-744, 1999.

[5] Ch. Koch and W. Molkenstruck, „Primary calibration of hydrophones with extended frequency range 1 to 70 MHz using optical interferometry", IEEE Trans. UFFC, vol. 46, pp. 1303-1313, 1999.

[6] R.A. Smith, „Are hydrophones of diameter 0.5 mm small enough to characterize diagnostic ultrasound equipment?", Phys. Med. Biol., vol. 34, pp. 1593-1607, 1989.

[7] R.C. Preston, D.R. Bacon, and R.A. Smith, „Calibration of medical ultrasonic equipment – procedures and accuracy assessment", IEEE Trans. UFFC, vol. 35, pp. 110-121, 1988.

[8] B. Zeqiri and A.D. Bond, „The influence of wavefront distortion on hydrophone spatial averaging corrections: theory and measurement", J. Acoust. Soc. Am., vol. 92, pp. 1809-1821, 1992.

[9] E. Radulescu, P. Lewin, A. Goldstein, and A. Novicki, „Hydrophone spatial averaging corrections from 1 - 40 MHz", IEEE Ultrason. Symp. Proc. 2000, pp. 1685-1688.

[10] T. Boutkedjirt and R. Reibold, „Reconstruction of ultrasonic fields by deconvolving the hydrophone aperture effects. I. Theory and simulation", Ultrasonics, vol. 39, pp. 631-639, 2002.

[11] T. Boutkedjirt and R. Reibold, „Reconstruction of ultrasonic fields by deconvolving the hydrophone aperture effects. II. Experiment", Ultrasonics, vol. 39, pp. 641-648, 2002.

[12] J.D. Gaskill, „Linear systems, Fourier transforms, and optics", John Wiley & Sons, New York, 1978.

[13] R. Bracewell, „The Fourier transform and its application", McGraw-Hill, New York, 1965.