The receiving range of sound field measurements in cavitating media: Definition of an effective distance

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ABSTRACT
Sound field measurements are widely used for the quantitative description of cavitation processes. For practical purposes it is important to know how local a sound field measurement information is, and therefore a technique is presented which allows the determination of the receiving range of such a measurement. The sound field is detected by two calibrated, similar hydrophones, mounted face to face in the cavitation cloud. The distance between the hydrophones is varied and the correlation between the two time-dependent signals is analyzed in the frequency domain defining a local parameter. The dependence of this parameter on the distance between the hydrophones describes the receiving range of a sound field measurement by means of a characteristic distance. The technique was applied to two different cavitation applications, and effective distances in the range 1 - 3 mm were obtained. It is shown that the spatial resolution of a sound field measurement in a cavitation field is determined by the hydrophone size and does not depend on the cavitation conditions if at least a medium cavitation activity is provided.

1. INTRODUCTION
The quantitative description of cavitation and its effects is a key element for the optimum use of cavitation in technical and medical applications. Problems such as the scale-up of sonochemical devices to large-scale vessels [1] or the improvement of the cleaning efficiency in an ultrasonic cleaner [2] require the careful investigation of quantitative parameters relevant to both, the sound field and the intended cavitation effect. The sound field is of particular importance because it is the driving force of all processes and the bubbles themselves emit secondary sound fields carrying information on the status of the bubble oscillation and the fluid streaming around.

Sound field measurements recently carried out with high spatial resolution, using small hydrophones and fibre-optic sensors [3], showed detailed spatial structures for the fundamental and also for the subharmonics and broadband noise as typical cavitation markers [4]. This result had not been anticipated because most of the sound is produced by the bubbles themselves and is emitted omnidirectionally, and this effect should blur a spatially resolved sound field measurement. This is especially the case for the standing wave structures observed not only for the fundamental, but also for the subharmonic or even for the noise power at MHz-frequencies. Since no resonance condition holds for these parameters, a more uniform distribution was expected. The results led to the conclusion that cavitation markers such as subharmonic or cavitation noise power are generated very locally at a site and that they have a short range of influence on a sound pressure detector. This range of influence defines, however, the extent to which a sound field measurement can be used to determine the local activity of cavitation. For practical purposes it is important to know how local a sound field measurement information is, and a quantitative investigation of the effect is required and presented in this paper.

The determination of such a range of influence, i.e. a receiving range, would require interrogating a particular bubble or small bubble group at an exactly known position in the cloud by a sound field detector [5]. By moving the detector while analyzing the output, it becomes possible to search for the specific signal from the addressed bubble or bubble group. Due to the stochastic character of cavitation processes, such a method is, however, not feasible in an extended bubble cloud. Another possible method would be to exploit a characteristic signal
instead of marking a particular bubble. In this case, the sound field within a bubble cloud is detected by two hydrophones, and both measured signals are compared to find similar or even equal signal contributions, for example by the application of correlation techniques. It is assumed that equal signals stem from the same source and the investigation of the correlation between the two hydrophone signals in dependence on the distance between the detectors gives an insight into the receiving range of the hydrophones.

In this paper, the experimental implementation of this method is presented and applied to two different practical cavitation fields. A local parameter is defined that describes the similarity of the two detected hydrophone signals which is investigated in dependence on the distance of the hydrophones. By using a fitting procedure, a characteristic distance is found which describes the range of the similarity between the signals that can be interpreted as the receiving range of sound field detection.

2. METHODOLOGY AND EXPERIMENTAL SETUP

2.1 Principle of the method
The sound field in a cavitation bubble cloud is detected by two calibrated, similar hydrophones, mounted face to face within the cloud (Fig. 1). The two measured signals are quite different from each other because every hydrophone is surrounded by different bubbles which emit different sound fields in addition to the driving field. If the distance between the hydrophones is not too great, similar contributions in both hydrophone measurement signals occur because they stem from the same bubbles situated at the symmetry plane perpendicular to the hydrophone axis exactly at the centre point between the hydrophone acoustic centres. If the distance between the hydrophones is increased, the similar signal contributions will decrease because of, e.g. absorption and scattering losses, but also because many other bubbles enter between the hydrophones which are ‘louder’. By this decrease, a receiving range of the sound field measurement can be defined. If it is not possible to find similar contributions in the hydrophone signals any more, it should just as well be impossible to measure an acoustic cavitation marker from the bubbles at the symmetry plane.

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J_{12}(d) = \int \frac{C_{xy}(f)df}{L} \quad L = 1,5 \text{ MHz}
\]

Figure 1. Scheme of the determination of the local parameter \(J_{12}\). Hyd: Hydrophone, Amp: amplifier, FIR: finite impulse response digital filter, \(f\): frequency, \(M_{oc}\): open-circuit end-of-cable sensitivity, \(C_{xy}\): coherence, \(P_{xy}\): cross spectrum, \(P_{xx}\), \(P_{yy}\): (aut-) spectrum

For a quantitative and experimental verification of this method, the hydrophone signals were amplified (Fig. 1) and detected by means of a digital oscilloscope, and the data were transferred to a computer. Both hydrophones were calibrated in the frequency range 0.1 - 5 MHz by means of a time-delay spectrometry (TDS) technique [6]. From the calibration data, a digital filter was calculated and the hydrophone data were corrected using a deconvolution method in the time domain. For comparing the two hydrophone signals, the coherence was determined [7] which provides a spectrally resolved information about the correlation between the two hydrophone signals. To define a single local parameter, the coherence was integrated over a particular frequency range to account for all events contributing to the cavitation-specific signal parts (Fig. 1).
The local parameter $J_{12}(d)$ describes the dependence of the correlation between the hydrophone signals on their distance and can be exploited for the determination of the receiving range of a sound field measurement. To describe this range quantitatively, a function of the form

$$J_{12,F}(d) = J_0 + A \cdot e^{-d/d_{1/e}}$$

was fitted to the data and two values of a characteristic distance were deduced: the distance $d_{1/e}$, where the local parameter decreases to $1/e \times (J_{12,F}(0) - J_{12,F}(\infty)) = 1/e \times A$, and $d_{10} = -d_{1/e} \times \ln 0.1$, where the local parameter reaches 10% of $A$.

2.2 Experimental set-up: Generation of the cavitating field

All measurements were carried out in a large tank 2.0 m in diameter which was filled with tap water to a level of 0.8 m (Fig. 2). At the tank centre, where the ultrasonic source was mounted perpendicular to the water surface, a plastic bag filled with 120 l of deionised water was inserted to allow the preparation of different water conditions without changing all water in the tank. The direction of the transducer vibration and the axis was set perpendicular to the water surface and defines the z-axis of the coordinate system chosen. The zero-point was given by the water surface.

![Diagram](image)

Figure 2. Experimental setup: Hyd: Hydrophone, Amp: amplifier, D-scope: digital oscilloscope, Gen: signal generator

Two different ultrasound sources were used, a sonotrode having a diameter of 6 mm and a fundamental frequency of 20 kHz (UW 2070, Bandelin GmbH, Germany), and two high-power transducers 45 mm in diameter (39 kHz) similar to devices used in a commercial cleaning bath (TI-H 5, Elma GmbH, Germany). Free-field conditions were chosen to obtain a spatially extended and homogeneous cavitation zone without a locally high or low bubble concentration from standing waves being always present in the application containers. The devices were driven by a high-power audio amplifier (TA-500, Thomann, Germany), using custom-made matching transformers.

For the hydrophones a PZT plate with a diameter of 3 mm and a resonance frequency of 20 MHz was glued to a brass cylinder (Ø 3 mm) which acted as inner electrode. The cylinder was inserted into a brass tube (Ø 8 mm) flush to the end, and small plastic rings were used as spacers. The PZT element and the spacer were covered with a thin layer of conductive epoxy resin forming the outer electrode and together with the brass tube, a completely electrically shielded design was obtained. The hydrophones were mounted horizontally into the tank and adjusted by hand-driven translation stages. Beginning at the point where the hydrophone faces meet exactly on the transducer symmetry axis in z-direction, the distance between the hydrophones was increased by moving the two devices step by step away from each other. All
hydrophone signals were acquired by a digital oscilloscope (TDS 3032B, Tektronix, USA), and at every distance point, eight independent measurements of 10000 sample points (at 5 MS/s) were captured. The data were processed with a Matlab<sup>TM</sup> computer code.

3. EXPERIMENTAL RESULTS

In Fig. 3 a typical measurement result is depicted for the sonotrode at a low cavitation level, just when the characteristic audible noise started. The upper plot shows the coherence as a function of the hydrophone distance, and values between 0.5 and 1 (maximum correlation) can be observed at low distances. As expected, the values decrease with increasing distance between the hydrophones, which is to be seen especially in the lower plot where the local parameter is depicted in dependence on distance \(d\). Since the cavitation level is not high, the decrease is, however, moderate.

![Graph of Coherence and Local Parameter](image)

Figure 3. Coherence (upper plot) and local parameter (lower plot) for the sonotrode at low cavitation level (level 2) in deionised, air-saturated water with detergent.

The decrease of the local parameter in Fig. 3 is moderate because of the low cavitation level and for comparison, Fig. 4 shows a result for the sonotrode at a higher driving level. Here the decrease is quite steep and can be approximated by a function following eq. (1) given as example in the plot, and the characteristic distances are \(d_{e} = 2.2\) and \(d_{10\%} = 4.9\).

To investigate whether the local parameter depends on the cavitation activity, the characteristic distances were determined as a function of the driving power. In Fig. 5 \(d_{e}\) and \(d_{10\%}\) are depicted in dependence on the driving level for the bath transducers. At level 1, no decrease (no fitting impossible) and at level 2 only a very slight decrease of the local parameter was observed. Beginning at level three, \(d_{e}\) suddenly drops down to a range of 1 - 3 mm and the values remain constant in this range even when the driving level is further increased, with the exception of a slight increase. During the experiments, the onset of the transient cavitation could be clearly detected by the onset of a characteristic audible noise and by the appearance of cavitation markers in the hydrophone signals between driving level two and three. The sudden decrease in \(d_{e}\) is related to the onset of the cavitation, showing that the local range of measurement is in the range of 1 - 3 mm within a cavitation field.
Figure 4. Coherence (upper plot) and local parameter (lower plot) for the sonotrode at a higher cavitation level (level 5) in deionised, air-saturated water with detergent.

Figure 5. Characteristic distances as a function of driving level for the bath transducers in deionised, air-saturated water with detergent.

DISCUSSION AND CONCLUSIONS

The receiving range of a sound field measurement in a cavitating medium was investigated by comparing the hydrophone signals measured at different distances from each other. A correlation method determined similar signal contributions, and characteristic distances were
defined using a local parameter. If no correlation exists, no sound field information from the point exactly half way between the hydrophones reaches the detectors. If a collapsing bubble is assumed at this position, acting, e. g., on a surface for cleaning or on a biological cell for sonoporation, no acoustic information about these processes can reach the acoustic detector for registration or investigation. In a practical situation, only events within a sphere with a radius of $d_{1/e}$ could influence a sound field measurement at the centre of the sphere and generate characteristic signal patterns which could be observed for a quantitative description of the cavitation event. Based on the assumption of loss of correlation, $d_{1/e}$ can be defined as the characteristic local range of a sound field measurement. During the experiments, the values for $d_{1/e}$ were in the range 1 - 4 mm for significant cavitation activity. Hydrophones commonly used for sound field measurements in technical ultrasound are underwater sound devices with an active diameter of 4 - 9 mm or even more [3]. They are larger than the characteristic receiving ranges obtained in this study. Thus, the spatial resolution of a sound field measurement in a cavitation field is determined by the hydrophone size and does not depend on the cavitation conditions if at least a medium driving level is provided. This conclusion is in agreement with previous results [3], where detailed spatial structures for all sound field parameters were found.

The found characteristic receiving ranges of sound field measurements are important for practical applications. In particular, investigations for determining optimum processing positions require reliable values for the local uncertainty of the measurements of cavitation markers. From this study it can be concluded that common hydrophones provide a sufficient spatial resolution which is defined by their outer dimensions. This result may help to advance the use of sound field measurements for cavitation quantification.

References:


