

Bubbles as hydrophones

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Introduction

Direct acoustic pressure measurements in cavitating liquids are often difficult: pressure sensors in form of standard hydrophones are typically invasive and might disturb the cavitation bubble field significantly (e.g. by attracting and attaching bubbles), and the cavitation can have erosive and destructing effects on the sensors. Furthermore, the presence of bubbles is an inherent inhomogeneity which leads to high fluctuations of the sound field in space and time. To cope with this, spatial and temporal averaging is often employed to obtain useful pressure data. However, sometimes less or non-invasive pressure sensors of high spatial and temporal resolution are demanded, for example to determine the true local acoustic pressure amplitude acting on individual bubbles in a bubble cloud or cluster. Sensors of choice are fine needle hydrophones or fiber optic probes which, however, have the drawbacks of high risk of damage and, for the optic probes, low recording sensitivity. For some types of problems, a way out could be the direct fitting of acoustic pressure to high-speed observations of individual bubble oscillations. Attractive sides of this idea to use the cavitation bubbles themselves as hydrophones are the non-invasiveness and the high resolution, and this method has already been applied successfully for laser-induced bubbles [1] and in single-bubble traps [2]. The suitability in multi-bubble environments has not yet been demonstrated. Here we sketch some background of the method and show two examples.

Method

The idea consists of a numerical fit of recorded oscillation and potentially also translational bubble dynamics. Necessary (and sometimes sufficient) fit parameters are equilibrium bubble radius R_0 and local (fundamental) driving pressure amplitude p_a . For taking into account the translational motion, some assumption or information on the local acoustic pressure gradient is needed as well. The success of the method relies mainly on (i) accurate observational data, (ii) a sufficiently complete fitting model, and (iii) a converging fitting procedure. To ensure (i), a transparent liquid is mandatory as well as a recording frame rate reaching or superseding the acoustic frequency. A certain amount of undersampling can be tolerable (employing back projection onto a single period) if the bubble oscillation / translation is stationary for some driving periods, but in many cases the stationarity is limited by collision with neighbor bubbles. In any case, the faster the recording, the more accurate and reliable are the results. As a model (ii), spherical bubble ODEs of Rayleigh-Plesset type

augmented by a coupled translation equation [3] are probably the best compromise between complexity and accuracy. Any extended model including non-spherical components will suffer from both additional need for extracted observational data and blow-up of fitting parameters. The latter appears as well as a problem if a non-trivial sound field is included, i.e., anything else but a sinusoidal fundamental frequency driving pressure. Still, the method might be suited for a limited amount of harmonics, in particular if positional or translational data is recorded [4]. The fitting (iii) might use a full radius-time curve plus position over time (if available), or just main observables like maximum and minimum bubble sizes and their respective phases, numbers and height of afterbounce oscillations, etc. Of course, the existence of a perfect fit cannot be expected as the model is idealistic, and system and data are noisy. Therefore finding a suitable measure of the fit quality and the tolerance margins might be problematic. Furthermore, due to the nonlinearity of the underlying equations, the radial motion is not harmonic (otherwise a simple determination of maximum and minimum radius would be sufficient), and uniqueness of the solution is not ensured. Thus difficulties might arise from non-smooth “fitness landscapes” in parameter space, for instance because of hysteresis and multiple solutions. For the examples shown, a fit “by hand” was done using parameter plane diagrams of maximum radius as well as stability regions of the spherical bubble shape [5]. For future automatic fit procedures, the mentioned issues have to be addressed, and additionally a good initial parameter guess might be necessary.

Examples

We employ the method to bubble oscillations below a sonotrode horn tip working in the 20 kHz frequency range. In such a set-up, bubble clouds directly in front of the tip can dampen the sound field by absorption and scattering, and estimated pressure values obtained from the analytic formula for the symmetry axis of a circular piston source can be much too high [6,7].



Figure 1: Pseudo-streak image of bubbles in water below a sonotrode tip driven at 20 kHz (subsequent vertical frames recorded at 250 kfps corresponding to 12.5 frames per driving period; exposure time 1 μ s, image height 0.5 mm.) Note the lower bubble which is oscillating strongly in volume and jumping upwards during the collapse phase.

The first data are recorded in water with a frame rate of 12.5 images per acoustic period, and they show a bubble oscillating and translating upwards to the horn tip, see [8] and Fig. 1. From this image series a radius-time curve and a position-time trace are generated shown in Fig. 2(top). Fitting by a Keller-Miksis model and an analytic piston source field (on the symmetry axis) results in reasonable agreement of both oscillation and translation for $R_0=15\mu\text{m}$ and $p_a=150\text{kPa}$, see Fig. 2(bottom). This means an effective sound pressure of only about half the value derived analytically from the actually observed sonotrode tip velocity, the reduction being caused apparently by absorption and scattering by other cavitation bubbles.

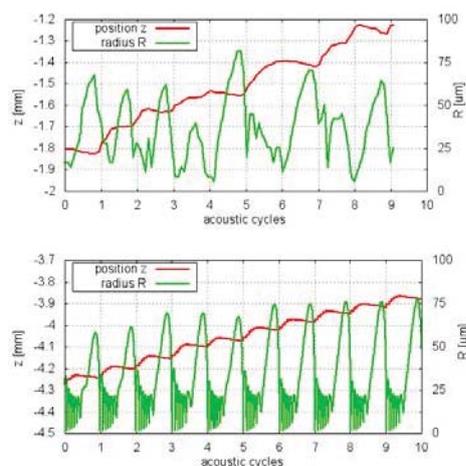


Figure 2: Observed (top) and fitted (bottom) dynamics of the lower bubble in Fig. 1, including radius R (green) and position z (red) vs. time (acoustic cycles).

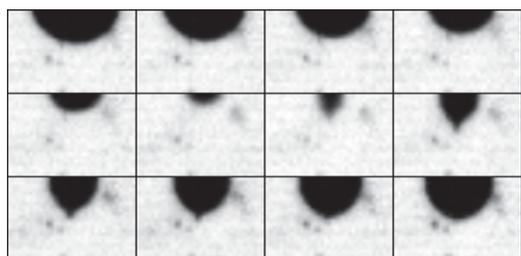


Figure 3: Part of the image series of a bubble below a sonotrode tip in sulfuric acid, driven at 23 kHz (recorded with 775 kfps; exposure time $1.3\mu\text{s}$, image width 0.42mm). The bubble is moving downwards (away from the tip).

The second example shows a single bubble below a similar sonotrode in sulfuric acid, now at higher spatial and temporal resolution (Fig. 3). The volume oscillation modality (no afterbounces after the intense collapse) and the translation including downward jumps can well be modeled by a fit presented in Fig. 4 which uses a piston source field, $R_0=64\mu\text{m}$, and $p_a=75\text{kPa}$. The resulting pressure amplitude is surprisingly low, as the bubble is nevertheless supposed to emit sonoluminescence. No sonotrode tip velocity was recorded here to estimate shielding, but from the fit a bubble volume compression rate $(R_0/R_{\min})^3=570$ and a maximum translation velocity (during the collapse jump) of about 100m/s can be derived. These “semi-experimental” values can serve, for instance, as a reference for more detailed

analysis of the bubble interior and its shape in the collapse phase, e.g. by non-spherical numerical models employing BEM or VoF methods. Note the second co-existing solution (dashed lines in Fig. 4) which appears for different initial conditions.

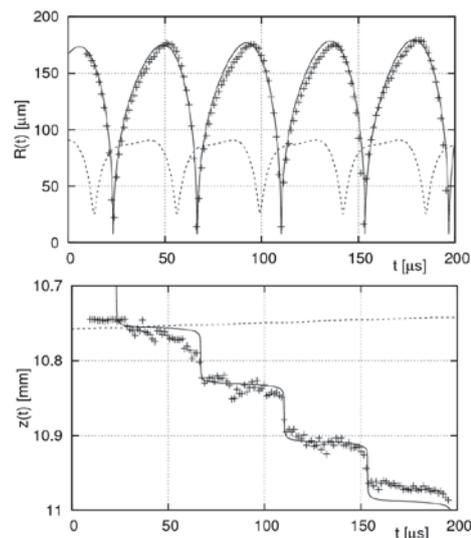


Figure 4: Comparison of experimentally measured values (crosses) and best numerical fit (lines) for radius R vs. time (top) and position z vs. time (bottom) for the case of Fig. 3. The dashed lines correspond to a second solution of the fitting Keller-Miksis equation for identical parameters.

Conclusion

While numerical fitting of single bubble dynamics in multi-bubble environments might have some pit-falls, it proves to be a reasonable method for acoustic pressure measurements in special cases. For instance, the method has been shown above to work for bubbles in sulfuric acid where no direct hydrophone measurements were possible because of the aggressive liquid. Future applications might give additional quantitative information on effective sound fields in bubble clouds and structures occurring in acoustic cavitation. Such data is needed, for instance, for validation of sound wave propagation models in bubbly liquids and for realistic modeling of the attenuation due to the bubbles.

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