Controllable acoustic bubble traps

H. Söhnholz, T. Kurz, W. Lauterborn
Universität Göttingen, 3. Phys. Inst., 37077 Göttingen, Germany, Email: hsoehn@physik3.gwdg.de

Introduction

Acoustic bubble traps are used to levitate an oscillating bubble at a fixed position near the pressure anti-node of the sound field. In this way the bubble dynamics and light emission (single bubble sonoluminescence, SBSL) can be investigated with high resolution [1, 2]. Typically, to obtain high pressure amplitudes, a high-Q resonance of the trap's container is exploited. This makes the trap susceptible to changes of external parameters like the temperature. Furthermore, the back-reaction of the bubble on the container may become large, making it difficult to maintain constant driving conditions when the bubble parameters change. In this paper the construction of bubble traps with medium- to low-Q resonators utilizing flexural disk and sandwich transducers is investigated. One design goal is to be able to control the bubble position to some extent by suitable driving. The transducers are operated at frequencies of about 20 kHz and are designed with the aid of FEM simulations. The sound pressure inside the water-filled prototypes is measured with a hydrophone. The transducer displacement is obtained from measurements with a vibrometer.

Experimental setup

The experimental setup is shown in Figure 1.
A nanosecond laser pulse is focussed into a cuvette to produce a single bubble by laser breakdown in water. The cuvette serves as a bubble trap due to the ultrasonic field inside that is generated by transducers attached to it. A trapped bubble is illuminated with an LED flasher and images are taken with a CCD camera at short exposure times of a few microseconds.

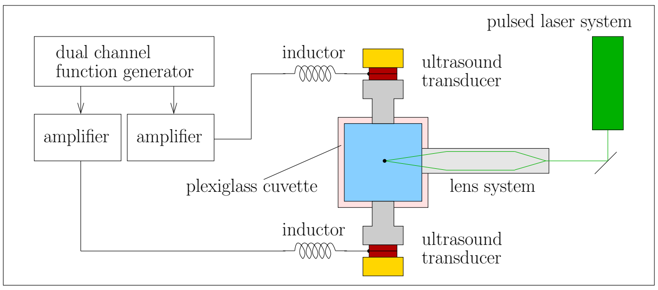

Figure 1: Experimental setup for the investigation of single bubbles. The imaging optics is not shown here.

The bubble trap

For the investigation of single bubbles an acoustic bubble trap is a valuable tool because an oscillating bubble can be levitated at a fixed position near the pressure antinode [3].

The bubble trap used in this experiment (Figure 2) is a cuvette made of plexiglass measuring 50 mm × 50 mm × 50 mm inside with the walls being 10 mm thick. In each of the six walls there is a circular port for mounting transducers and imaging optics. Optical windows and flexural disk transducers are clamped by a brass flange. Sandwich transducers are seated in a brass tube which is attached to the cuvette. One side wall of the cuvette is mounted onto a stand. Rubber washers are used for acoustic decoupling of the bubble trap from the stand.

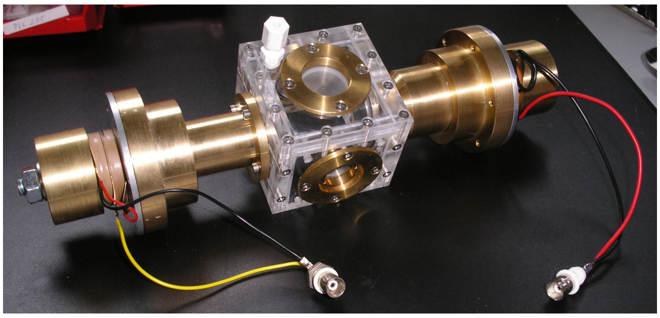

Figure 2: Photograph of the bubble trap with two sandwich transducers attached.

The cuvette is filled with clean de-ionized water which is filtered by a membrane filter (pore size 0.2 μm). Before filling the water into the cuvette it is degassed using a vacuum pump to reach the dissolved gas content needed for stable SBSL.

The ultrasonic transducers are described in a separate section (see below). The excitation signals are generated by a dual channel function generator (Tektronix AFG 3022). Each of the two channels is connected to a separate amplifier (2× Krohn–Hite DC-500 KC). The output signal of the amplifiers is fed to the transducers with an inductor wired in series (see Figure 1).

The sound pressure inside the bubble trap is measured by a hydrophone (Reson TC4038). The transducer displacement is obtained from measurements with a vibrometer (Polytec OFV 3001 controller + OFV 303 sensor head).

Pulsed laser system

A pulsed Nd:YAG laser system (Quantel Brio) is used to seed bubbles in the trap. The laser pulses with a pulse width of 4 ns and a wavelength of 532 nm are focussed into the bubble trap by a lens system with one of the lenses mounted directly into a wall of the cuvette. Using this nanosecond laser system bubbles with radii of about 1 mm can be generated with high reproducibility.

Ultrasonic transducers

The sound field inside the bubble trap is generated by two transducers mounted as shown in Figure 1. By introducing a phase shift in their excitation signals the pressure anti-node of the sound field, and thereby the bubble position, can be shifted to some extent.

The transducers are designed to have a resonance frequency close to the frequency corresponding to the eigenmode of the cuvette with one pressure anti-node at the center. Electrical impedance matching of the amplifier to the transducer can be achieved by adding an inductor $L = (\omega^2 C_p)^{-1}$ connected in series. In this relation ω denotes the angular frequency of the excitation signal and C_p is the capacitance of the transducer. Two types of composite transducers are investigated for generating the low ultrasonic frequencies of about 20 kHz.

Sandwich transducers

The sandwich transducers consist of two piezoelectric rings, a brass backing mass and an aluminum front piece (Figure 3). The transducer has a cylindrical shape and is rotationally symmetric to the axis shown in the figure (dotted line). Lengths and diameters of the various parts are denoted in the figure by l and d, respectively. Prestress is applied to the piezoelectric rings with a steel screw. The aluminum front piece is shaped as a stepped horn to match the acoustic impedance of the transducer to the load impedance of water.

The design of a sandwich transducer including the acoustic impedance matching is performed according to Sindayihebura et al. [4]. They present an analytical model that takes into account the mechanical and electrical properties of the different transducer parts to determine the optimal dimensions for maximum displacement.

A resonance frequency of 18.5 kHz (an estimate for the lowest resonance frequency of the cuvette) is chosen for the calculations of the sandwich transducer dimensions. The model [4] yields $l_b = 25$ mm, $l_1 = 22$ mm, $l_2 = 60$ mm for $d_2 = 23$ mm, $d_1 = d_b = 45$ mm. These results are used to construct the sandwich transducers investigated here.

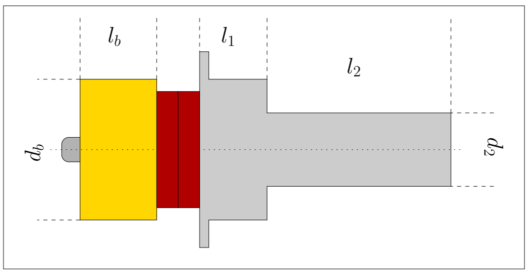

Figure 3: Sandwich transducer (cross-sectional view).

Flexural disk transducers

The flexural disk transducers are made of a piezoelectric disk of radius r_p and thickness t_p glued onto a circular membrane of radius r_m and thickness t_m with a layer of epoxy (Figure 4). Membranes made of steel and glass are used.

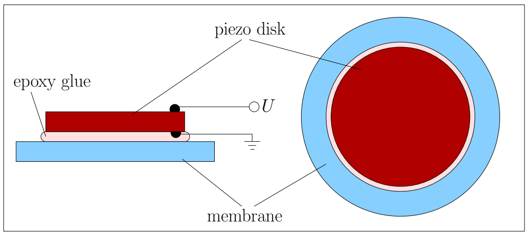

Figure 4: Cross-sectional (left) and top view (right) of a flexural disk transducer.

The deflection of the membrane depends on the thickness ratio t_m/t_p. Wang and Cross [5] found that maximum deflection can be achieved with a thickness ratio of

$$\left(\frac{t_m}{t_p}\right)_{\max} = \sqrt{\frac{E_p}{E_m}} \tag{1}$$

where E_m and E_p is the Young's modulus of the membrane and the piezoelectric layer, respectively. The piezoelectric disks glued to the membrane have a thickness of $t_p = 1.0$ mm.

With $E_m = 200 \cdot 10^9\,\mathrm{N/m^2}$ for a steel membrane and $E_p = 110 \cdot 10^9\,\mathrm{N/m^2}$ one obtains a membrane thickness of $t_m \approx 0.7$ mm. A steel membrane with $t_m = 0.6$ mm and $r_m = 15.75$ mm is used as this was at hand. The piezoelectric disk glued to the membrane has a radius of $r_p = 8$ mm.

In addition a flexural disk transducer with a glass membrane ($t_m = 0.5$ mm, $r_m = 15$ mm) has been built. The piezoelectric disk of this transducer has a radius of $r_p = 10$ mm.

Simulation of the bubble trap

All simulations are carried out with the FEM software *Comsol*. Eigenmodes and eigenfrequencies of the cuvette are determined by solving the Helmholtz equation in three dimensions with appropriate boundary conditions.

The bubble trap model consists of the plexiglass walls ($\rho_1 = 1190\,\mathrm{kg/m^3}$, $c_1 = 2750$ m/s) and the water inside ($\rho_0 = 998\,\mathrm{kg/m^3}$, $c_0 = 1481$ m/s). The outer surfaces of the walls are considered sound soft. This results in an eigenfrequency of 18.2 kHz for the eigenmode with one pressure anti-node at the center of the bubble trap.

The simulation of the ultrasonic transducers involves calculation of the deformation of the piezoelectric elements due to an applied electric potential using the piezoelectric equations. Furthermore, the deformation of the attached head and backing masses are computed using the stress–strain relations. All materials are considered isotropic. Eigenmodes and resonance frequencies of the transducers are computed in the simulation.

Results

The sound pressure values measured with the hydrophone are to be considered an estimate because calibration data are only available down to 50 kHz.

Flexural disk transducers

Figure 5 shows the resonance curve of sound pressure inside the cuvette, and Figure 6 that of the membrane deflection, as measured for a flexural disk transducer made of glass. The simulation of this transducer ($t_m = 0.5\,\text{mm}$, $r_m = 15\,\text{mm}$) gives an eigenfrequency of 5.9 kHz. Changing the thickness of the glass membrane to $t_m = 2.0\,\text{mm}$ leads to an eigenfrequency of 21.0 kHz. For a steel membrane ($t_m = 0.6\,\text{mm}$, $r_m = 15.75\,\text{mm}$) an eigenfrequency of 6.6 kHz is calculated.

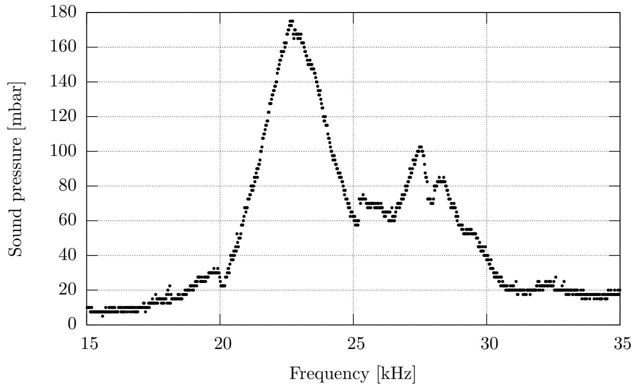

Figure 5: Resonance curve of the cuvette driven by one flexural disk transducer with a glass membrane ($t_m = 0.5\,\text{mm}$, $r_m = 15\,\text{mm}$).

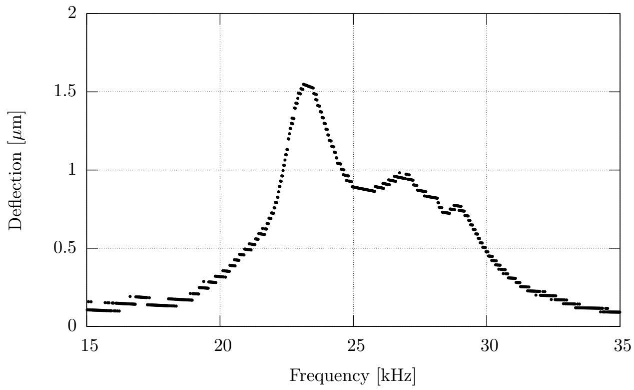

Figure 6: Deflection of the flexural disk transducer with a glass membrane ($t_m = 0.5\,\text{mm}$, $r_m = 15\,\text{mm}$) as a function of the excitation frequency.

Sandwich transducers

The simulation of the sandwich transducer with the dimensions obtained from the analytical model resulted in an eigenfrequency of 18.2 kHz which, contrary to the thin flexural disk transducers, is close to the prescribed value. A resonance curve of the pressure inside the cuvette driven by one transducer of this type, measured with the hydrophone, is shown in Figure 7.

The experimental Q-factors for the plexiglass cuvette with a sandwich and with a flexural disk transducer are given in Table 1. For comparison, the Q-factor of a glass cuvette as it is usually used in SBSL experiments, is also given in Table 1. Due to the lossy cuvette walls the resonance is broadened considerably compared to the glass cuvette which was one design goal.

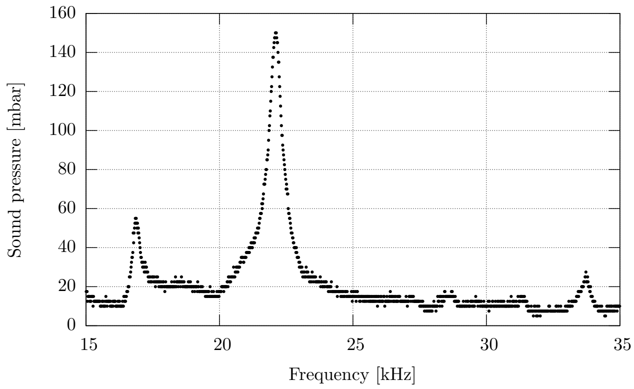

Figure 7: Resonance curve of the cuvette driven by one of the sandwich transducers.

Cuvette	Transducer	f_0 [kHz]	Q
Plexiglass	Sandwich	22.1	14.4
Plexiglass	Flexural disk (glass)	22.7	3.7
Glass	Piezo disk	42.4	82.9

Table 1: Quality factors of the plexiglass bubble trap with different transducers mounted to it. The quality factor of a glass cuvette with a piezoelectric disk glued to the bottom is given for comparison.

We now turn to the complete bubble trap with two transducers. Figure 9 shows the simulation geometry of the system, comprised of the two synchronously driven transducers and the water-filled cuvette, together with the simulation results for pressure and displacement (colour coded). The numerical analysis yields a resonance frequency of 24.9 kHz for the eigenmode with the pressure anti-node at the center.

The sound pressure field inside the cuvette shown in Figure 2 is measured with a hydrophone along the common axis of the two transducers for two different phase shifts of the driving voltages. The results for phase shifts $3\,°$ and $-27\,°$ are shown in Figure 8. The sound pressure curve shows the expected single maximum at the center. The position of the pressure anti-node is shifted by about 2 mm. This is considered to be sufficient to position the bubble in an experimental observation.

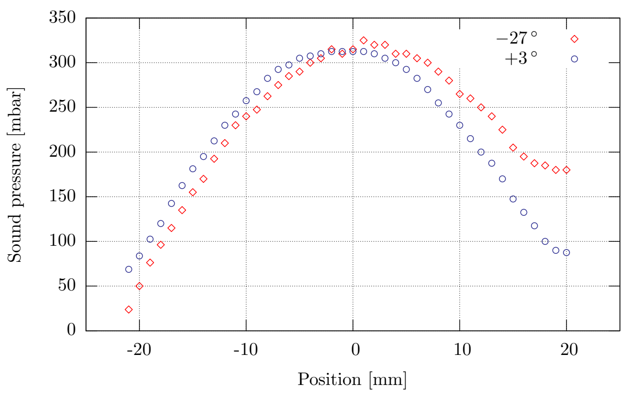

Figure 8: Sound pressure field inside the bubble trap with two sandwich transducers attached for two different phase shifts at 23 kHz.

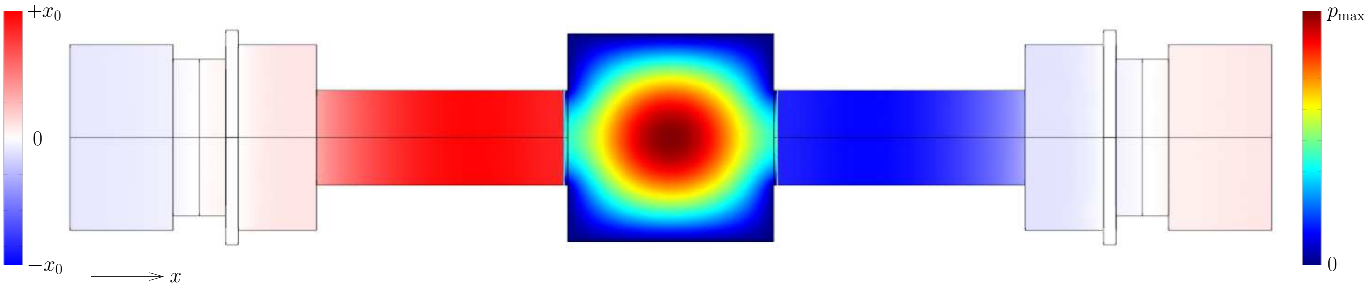

Figure 9: Sound pressure inside the cuvette and x-displacement of the two sandwich transducers attached to it at 24.9 kHz.

Conclusion

The simulation results show that the resonance frequency of the flexural disk transducers is much lower than the resonance frequency of the cuvette. The resonance frequency of the sandwich transducer is closer to the eigenfrequency of the cuvette and this transducer also leads to an increased Q-factor.

Bubbles have been trapped successfully with both types of transducers and the bubble position can be controlled by introducing a phase shift in the excitation signals.

In the future, images of the bubbles will be taken at different time delays after laser breakdown to obtain the temporal evolution of the bubble shape and position.

Acknowledgements

The sandwich transducers and the cuvette have been constructed and built by the mechanical workshop of the Drittes Physikalisches Institut.

We would like to thank Elma [6] for supplying the piezoelectric rings used in the sandwich transducers.

References

[1] W. Lauterborn, T. Kurz, R. Geisler, D. Schanz, and O. Lindau, 'Acoustic cavitation, bubble dynamics and sonoluminescence', Ultrason. Sonochem. **14**, 484 (2007).

[2] M. P. Brenner, S. Hilgenfeldt, and D. Lohse, 'Single-bubble sonoluminescence', Rev. Mod. Phys. **74**, 425 (2002).

[3] D. F. Gaitan, L. A. Crum, C. C. Church, and R. A. Roy, 'Sonoluminescence and bubble dynamics for a single, stable, cavitation bubble', J. Acoust. Soc. Am. **91**, 3166 (1992).

[4] D. Sindayihebura, L. Bolle, A. Cornet, and L. Joannes, 'Theoretical and experimental study of transducers aimed at low-frequency ultrasonic atomization of liquids', J. Acoust. Soc. Am. **103**, 1442 (1998).

[5] Q. M. Wang and L. E. Cross, 'Performance Analysis of Piezoelectric Cantilever Bending Actuators', Ferroelectrics **215**, 187 (1998).

[6] Elma Hans Schmidbauer GmbH & Co. KG, URL `http://www.elma-ultrasonic.com/`.