Acoustically driven cavitation cluster collapse in planar geometry

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We demonstrate the dynamics of arrays of transient cavitation bubbles exposed to a sound field in a planar geometry. Single, double, and complex configurations of cavitation bubbles are obtained by shaping a pulsed laser beam with a digital hologram and focusing it into a thin gap of liquid. The liquid is driven with an oscillating pressure field of variable phase and amplitude. We compare the dynamics of a single bubble recorded with high-speed photography with a two-dimensional Rayleigh model. For multibubble configurations we observe bubble-bubble interaction and coalescence which depends on the phase of the acoustic field. Larger clusters demonstrate drastically enhanced collapse for high-amplitude driving, enabling the study of artificial cavitation clusters under strong driving.

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I. INTRODUCTION

Cavitation describes the formation of mostly empty voids in liquids and their subsequent dynamics. The energy stored in the liquid when a cavity has reached maximum volume is focused to a very tiny spot during its subsequent shrinkage. This collapse of the cavity enables fascinating fluid physics such as rapid heating of the bubble interior, shock wave emission, and generation of photons [1–3].

The focusing of liquid energy by the collapsing bubble is responsible for cavitation erosion, which—for example—is causing damage in turbomachinery. On the beneficial side this ability to concentrate the energy of the liquid into small spots can be utilized for medical applications such as the destruction of kidney stones [4,5] or the treatment of tissues [6]. Some applications utilizing cavitation need to control the fine balance between the beneficial uses while preventing damage, for example, in ultrasound cleaning [7].

In general, a cavitation event is accompanied by the formation of many bubbles, and it is accepted that the mechanical effects can be grossly amplified due to their interaction. These so-called cavitation clusters or clouds have been studied particularly in greater detail in hydrodynamic cavitation. Their damaging potential is explained with a collective cavitation collapse front traveling from the rim of the cloud to its center [8–12]. This so-called bubbly shock wave emits and amplifies a pressure wave which is focused at the center of the cavitation cloud. A collective collapse of bubbles has been made responsible for the accident at Super-Kamiokande [13] and also for the damage found in spallation neutron sources [14].

In hydrodynamics cavitation, the positions of the cavities in the cluster are random and the number density is high; therefore, their dynamics may be modeled using a continuous distribution of bubbles. However, experiments have been conducted with well-defined configurations dating back to the ground laying work from the Cavendish laboratories, e.g., Refs. [15,16]. In those experiments, arrangements of cavities were cut into a layer of gelatin and were excited with a single shock wave. Under these high pressures gelatin becomes liquidlike, which allowed studying the collapse of the cavities with high-speed cameras. Other experimental realizations of multibubble cavitation are through nucleation from hydrophobic pits micromachined in surfaces [17], through laser-induced cavitation using a digital hologram [18], or the positing of bubbles using multiple spark discharges [19].

Simulation of the cavitation cluster dynamics assuming potential flow has been conducted by several groups. An axisymmetric code was compared with experiments by Bremond et al. [20], and larger and three-dimensional clusters have been modeled by Bui et al. [21] and Wilson et al. [22]. All simulations demonstrate that the outer bubbles in general collapse with a jet directed toward the center of the cluster.

In this work we report on cavitation bubbles created by focusing intense laser light into liquids. Laser-induced cavitation offers precise control over position and timing of the nucleation. Thus, they are specifically suited to be used in high-frequency sound fields where a phase synchronous generation is critical. Several groups have succeeded to enhance the collapse of a single laser-induced bubble in these pressure fields, e.g., to enhance the light emission upon collapse. In 2000 we reported on millimeter-sized bubbles driven at rather low frequencies [23] of a few kilohertz. Results for smaller bubbles created with a femtosecond laser driven at ultrasound frequencies are reported in Ref. [24]. Recent work to drastically enhance the collapse of a single laser-induced bubble loaded the bubble with a static pressure of 30 MPa and focused a spherical converging shock wave onto it [25]. Planar shock waves, in contrast, induce a high-speed liquid jet traveling in the direction of shock wave propagation [26,27]. Interestingly, a strong acoustic emission is recorded from the water hammer pressure, which is due to the liquid-liquid impact caused by the jet.

Here, we go one step ahead and study the amplified collapse not from a single bubble from an acoustic driven cluster of cavitation bubbles. The cluster is prepared with an array of laser foci while the bubbles are driven with an external acoustic field. The bubbles are generated within a thin...
liquid filled gap, i.e., an approximate planar geometry. We first test the effect of the sound field on a single bubble and then compare it with a simple model. Subsequently, we study a bubble pair and more complex configurations of bubble clusters.

II. EXPERIMENTAL SETUP

The key components of the experimental setup are a pulsed laser, a spatial light modulator (SLM), an inverted microscope, and a thin liquid film. The complete setup is sketched in Fig. 1. The laser used to create the bubbles is a frequency doubled Nd:YAG (Orion, New Wave Research, Fremont, CA, USA) with a 6 ns pulse duration. The energy of the pulse is controlled by the delay between the triggering of the flash lamp and the Q switch. Precise timing is achieved with a pulse delay generator (Model 575, Berkeley Nucleonics Corporation, San Rafael, CA, USA) which controls the timings of all the other components, i.e., high-speed camera, illumination shutter, and function generator. Since fluctuations in the laser energy lead to slight changes in the bubble size, we record in each experiment the energy of the laser pulse by sampling a portion with an energy monitor (XLE4, Gentec, Quebec, Canada). If the laser energy is not within a small percentage from a fixed value (stated below), the run is discarded.

To create multiple foci from a single laser pulse a digital hologram is projected onto the SLM. The SLM (Model LC-R-2500, Holoeve Photonics AG, Berlin, Germany) changes the phase of the incident light. To create the desired pattern at the focal plane of the microscope objective the digital hologram is calculated using the software provided by the SLM manufacturer from a digital image which marks the locations of the desired foci as single bright pixel values [18,29]. The pattern is projected into the liquid film with a 20× microscope objective of an inverted microscope (Olympus IX-71, Singapore).

The liquid film where the laser beam is focused is contained between a microscope slide and a cover slip separated by distance holders (strips of aluminum foil) fixing the height of the liquid gap to about 15 μm. We use aqueous magenta ink (refill ink) with a similar viscosity as water. A transducer (disk of 25 mm diameter and 2 mm height, Steiner & Martins, Miami, FL, USA) is glued with epoxy to the lower microscope slide and is driven directly with a power amplifier.

The sample is illuminated from the top with the microscope condenser optics. To prevent heating of the ink we use a homebuilt shutter, so that the sample is illuminated only for a few tens of milliseconds during the high-speed recording. The function generator (Model 33220A, Agilent, CA, USA) provides a burst of a sinusoidal signal which is amplified with an rf power amplifier (Model AG1006, T&C, Rochester, NY, USA) up to 400 V and is fed directly to the transducer. The pressure generated within the 15-μm-thick film is difficult to measure. Instead we measure the pressure just above the cover slip before the experimental runs while we monitor the pressure during the runs further outside. The latter is to make sure that the driving signal remains constant. Therefore, a PVDF-film-type hydrophone (polyvinylidene fluoride film, 3 mm diameter, RP acoustics, Stuttgart, Germany; not shown in Fig. 1) with a circular sensor surface of 3 mm diameter is brought close to the upper (cover) glass surfaces covering the liquid gap. The hydrophone is acoustically coupled to the glass surface with a drop of water.

The bubble dynamics is recorded with a high-speed camera (Photron SA 1.1, Japan). We operate the camera in such a mode to temporarily store the recordings for different runs before they are downloaded to a laboratory computer. In this way the experiment is automated to obtain a sufficient number of runs within the above-mentioned range of laser energies and for a sufficient number of different phases.

III. EXPERIMENTAL RESULTS AND DISCUSSION

We start with the simplest case of a single laser-induced cavitation bubble exposed to a sound field with varying phase and compared its dynamics to the bubble dynamics in the absence of the sound field. The radial dynamics of the bubble is compared with a two-dimensional Rayleigh equation. Then, we study the dynamics of arrays or clusters with two, five, and nine bubbles to learn about the effect of the sound field on their collective dynamics.

A. Single bubble

First we confirmed that the bubble dynamics is radially symmetric with a larger field of view and for slower framing
speed. Then we switched to a faster framing rate of 450 000 frames per second (fps). This allowed capturing of only the central slice. Figure 2(a) depicts horizontally arranged consecutive slices from the high-speed recordings taken in the absence of the sound field. Before we analyze and discuss the remaining data we compare the free expansion and collapse with a two-dimensional Rayleigh-type equation [1]:

\[
(R\dot{R} + R^2)\ln\left(\frac{R}{R_0}\right) + R^2 = \frac{P}{\rho},
\]

where \(R\) is the bubble radius, \(\rho\) is the density of the liquid, \(P\) is a constant pressure far from the bubble, and \(R_0\) is the distance at which the velocity of the induced flow vanishes [28].

It should be emphasized that this model is based on potential flow and ignores the effect of boundary layers. This limiting assumption can be advocated for sufficient short times of diffusive growth of the boundary layer [29].

We obtain \(R_0=376\ \mu m\) by fitting the measured dynamics (1) and using \(P=1\) bar as the atmospheric pressure. It is important to note that the model does not capture the initial vaporization of the liquid leading to high vapor pressure as well as the transition of the three-dimensional expanding bubble to a more planar shape. This happens in the very early state, and therefore we omit the first data point, i.e., we model from \(t=2.8\ \mu s\). It is important to note that the bubble wall velocity at this time cannot be deduced from the experiment since the bubble is decelerated by the atmospheric pressure. A velocity of \(dR/dt(t=2.8\ \mu s)\approx 6.3\ m/s\) is obtained from the fit which is 15% higher than the averaged velocity over the first two frames.

Previously we have shown [30] that the time from maximum bubble size to collapse of a bubble governed by potential flow in planar geometry is prolonged by a factor of \([\ln(R_0/R_{MAX})]^{1/2}\), thus with \(R_{MAX}=97\ \mu m\); this factor is approximately 1.15. This agrees with the expected value as the three-dimensional collapse time \(T_c=0.915R_{MAX}(\rho\gamma P)^{1/2}\).

Next we include the acoustic field in the model which modifies the bubble dynamics inside the liquid gap. Generally speaking, to increase the bubble lifetime the bubble has to be generated during the tensile phase of a low-frequency sound field, while to enhance the collapse a positive pressure has to limit the expansion and accelerate the shrinkage. Using a sinusoidal driving signal the range of optimum frequency \(f\), i.e., the one which has the largest effect on the bubble dynamics, is \((2T_{2D}^{-1} < f < (T_{2D}^{-1})^2\), where \(2T_{2D}\) is the lifetime of the bubble in the absence of acoustic driving [23], thus a frequency between \(f=24\ kHz\) and \(f=48\ kHz\) we selected a frequency of \(f=28.3\ kHz\) based on the mechanical and electrical resonance while making sure that the pressure variations were approximately harmonic. Therefore, the pressure signal is measured with a hydrophone on top of the upper cover slip. We expect that this measurement will give a good representation of the pressure signal, yet the amplitude may vary considerably as we measure in the acoustic near field of the radiating plate. These strong variations of the pressure amplitude with distance from the surface have been observed before [31].

To model the dynamics we replace the constant pressure term in Eq. (1) with a sinusoidal drive:

\[
P(t) = P_0 + P_A\sin(2\pi ft + \Phi),
\]

where \(P_A\) is the pressure amplitude and \(P_0\) is the static pressure of 1 bar, \(f=28.3\ kHz\) is the acoustic frequency, and \(\Phi\) is the phase of bubble generation. Due to the prevalent fluctuations of the pulse energy of Nd:YAG lasers, we monitored the laser energy of each bubble. Only bubbles whose laser energy is within a range of \(\pm 2.4\%\) from the energy of the bubble without acoustic driving [see Fig. 2(a)] are selected for the analysis.

The effect of the acoustic field with different phases on a single bubble is shown in Figs. 2(b)–2(i). We find that for cases (d) and (e) the lifetime of the bubble is shortened, i.e., phases between \(\Phi=-0.03\pi\) and \(\Phi=0.22\pi\), whereas the largest lifetime is observed for a bubble created at \(\Phi=0.97\pi\) [Fig. 2(h)]

To understand more the effect of phase on the acoustic driving we plot three selected radius versus time curves in Fig. 3(a) (filled symbols) and compare it to the unforced
bubble oscillation (open symbols). The symbols represent the experimental data and the solid lines are solutions to the model [Eqs. (1) and (2)]. The model has two variable parameters: the pressure amplitude \( P_A \) and the initial phase; the initial velocity \( dR/dt = 2.8 \mu s \) is taken from the experiment using the same 15% increased averaged velocity as in the absence of the sound field (see above). The free parameters of the model are the amplitude of the acoustic driving, \( P_A \), and a constant phase offset between experiment and simulations \( \Phi_0 \), with \( \Phi = \Phi_0 + (n-1)\Delta\Phi \), where \( n \) is the experimental run from 1 to 8 and \( \Delta\Phi = \pi/4 \) is the constant phase offset between the experimental runs in Figs. 2(b)–2(h). We obtain a best fit of the model [Eqs. (1) and (2)] with the experiment for a pressure amplitude of \( P_A = 0.2 \) bar. The error bars in Fig. 3(a) are representative for all data points and are due to the finite exposure time of 1 \( \mu s \) and the measurement error in determining the bubble radius.

Comparing the simulations and experiments we obtain an overall good agreement. The simulation suggests an increase in lifetime when the bubble is seeded during the tensile phase of the sound field, a shortening during the positive pressure phase, and only mild modifications when the bubble is nucleated at a later phase of the negative pressure. Increasing the pressure amplitude leads to strong nonlinearities in the measured sound field; this may be partly caused by cavitation in the coupling liquid or from the sound source itself. It is interesting to note that although we measure a pressure amplitude of 1.1 bar just above the cover slip a smaller pressure amplitude is used in the simulations; yet this difference is within the expected range because of the complex acoustic near field created by the oscillating glass substrate [31].

B. Bubble pair

Now we focus on the next most simple bubble configuration made of two bubbles. The initial distance of their centers is \( d = 23 \pm 4 \) \( \mu m \). In a previous study [29] we characterized this distance as the strong interacting regime, i.e., as the non-dimensional standoff distance \( \gamma = d/(2R_{MAX}) < 1 \). In this regime, during expansion the bubbles form a thin and flat film between them. This film formation is visible in the case of no-sound field of Fig. 4(a) (base case). The first frame (from left to right) is recorded 0.1 \( \mu s \) after the arrival of the laser pulses; the successive frames are taken at intervals of 2 \( \mu s \), i.e., 500 000 fps. Only experiments are selected where the laser energy is within \( \pm 3.7\% \) of the base case (no-sound field).

During the expansion of the bubbles (second frame), the flattened interface between the bubbles persists during the collapse process in frame 3. Already in the fourth frame the bubble has collapsed. We observe an intact boundary between both bubbles, indicating that the film has not ruptured. For bubbles at this close distance we expect a jetting flow traveling from both sides toward the center of the bubble pair. These counterpropagating jets may impact onto each other and reflect. However, because of the limited temporal and spatial resolution this jetting cannot be resolved. Expanding the bubble to a larger size and for a longer time using a sound field may increase the likelihood to rupture the film, e.g., to induce coalescence between the bubble pairs before they have collapsed. Due to the smaller size of the bubble as compared to Fig. 2, a higher frequency of \( f = 126.9 \) kHz is applied in the following experiments [Figs. 4(b)–4(f)]. Thus, about four frames cover one oscillation cycle of the sound field. For this experiment the sound field
pressure is increased; a peak pressure on top of the glass plate of 5.3 bar is measured.

The richness of the bubble dynamics in the presence of the sound field (Fig. 4) is worth a detailed look on the effect of the acoustic phase. Its value is stated in the first frame of each row in Figs. 4(b)–4(i) in units of $\pi$. Depending on this phase the duration of the first bubble oscillation is shortened [Figs. 4(b)–4(d) and 4(i)], remains unchanged [Fig. 4(k)], or increases [Figs. 4(f)–4(j)]. Figure 4(e) presents a particular interesting case. Here, we think that the bubble is hindered from a strong collapse between frames 2 and 3 due to the negative pressure, although the frame rate does not allow a definite statement. Yet, we base this hypothesis because a strong collapse would have lead to a translation of the bubble centers. This strong collapse occurs later when the pressure becomes positive again in frame 5, and then the bubble collapses and dissolves quickly.

In the absence of a sound field no afterbounces are observed; the vapor bubble recondenses and the bubble vanishes. However, with acoustic driving we find a single rebound for most of the cases. This can be explained, assuming that some gas or vapor in the bubble remains which acts as a nucleation site when the pressure drops back to negative values. During re-expansion the remains may show fragmentation. In particular in frame 6 of Fig. 4(g) complex fragmentation is observed, which may be caused by the impact of two opposing jets formed in the collapse between frames 5 and 6. These jets reflect upward and downward, while both bubble fragments expand leading to a 90° rotated configuration of the bubbles. In Figs. 4(i)–4(k) after collapse the right bubble is larger than the left bubble, although during expansion the left bubble seems to be slightly larger than the right bubble. The interaction between the bubbles during the collapse is not resolved. A plausible scenario could be that as the smaller bubble has collapsed first and it hinders during its rebound the growth of the larger bubble which is rebounding later [32].

We observe coalescence of the bubble pair only for a very narrow range of phases [Fig. 4(h)]. Indication for coalescence is that the thin film between the two bubbles has severely blurred (frames 3 and 4), is absent in frame 5, and the bubble becomes a single bubble after rebound (frame 7). The noncircular shape of the bubble in frame 6 of Fig. 4(h) may be due to surface oscillation. The rupture is happening during the late phase of bubble expansion. Possibly the thin-film drainage between the bubble is supported by the outward directed flow field created by the expanding bubble pair.

C. Five bubbles

As a more complex cavitation cluster we have chosen the five-on-a-dice pattern. This pattern in a three-dimensional geometry has been simulated by several groups, e.g., Chahine and Duraiswami (Fig. 10 in Ref. [33]), Bui et al. (Fig. 11 in Ref. [21]), and Wilson et al. (Fig. 1 in Ref. [22]) using boundary element for the first two and multipole methods for the last reference. The simulations of Chahine and Duraiswami [33] and Wilson et al. [22] predict a squarish inner bubble at maximum expansion surrounded by four rounder bubbles with a flattened surface close to the inner bubble. Indeed, this is what we see in the experiment presented in Fig. 5(a). During expansion frames 1 and 2 the outer bubbles are rounder. Their centers are not pushed outward, but the surface facing the central bubble is flattened. The outer bubble collapses first. The simulations [21,22,33] predict jets directed toward the central bubble in the later stage of collapse. Interestingly, in Fig. 5(a) (frame 3) the outmost part of the outer bubbles shows pronounced motion blurring which may be caused by a jet forming at that side. The collapse of the cluster starts from the outside and the central bubble collapses last. It seems that after the outer bubbles have collapsed the central bubble shrinks more rapidly than the outer bubbles. Unfortunately, the temporal resolution does not allow a detailed assessment. This is an important point as it has been suggested that the collapse of a bubble at the cluster center is amplified.

Adding a sound field, $f=125.8$ kHz, we can strongly alter the overall size and the lifetime of the cluster. The largest size is obtained at a phase of 0.75$\pi$ [Fig. 5(e)], while the shortest lifetime is obtained at 0 [Fig. 5(b)], which is about the expected phase difference of $\pi$. Yet we expect harmonic distortions of the driving sound field. Interestingly, the cluster lifetime can be considerably shortened compared to the no-sound case while a noticeable prolongation of the lifetime is not achieved. In Figs. 5(d) and 5(e), the cluster reaches a larger size, and it seems that the collapse proceeds faster in these cases.
they are followed by the remaining four bubbles on the periphery like in the case of the five-bubble array. Also, the bubbles are deformed; especially the one at the center has a square shape.

Although the bubbles in Figs. 6(f)–6(h) (frame 2) are slightly larger than the ones in Fig. 6(a) it seems that the lifetime of the bubble cluster can only be shortened using the sound field but not prolonged. This is due to the rather high frequency of the sound field. Yet, the collapse can be considerably shortened, which is most prominently demonstrated for the phases close to zero [Fig. 6(b)].

IV. CONCLUSIONS

We have demonstrated single and bubble cluster dynamics in the absence and with an additional sound field. The bubbles are created with a laser within a narrow gap and through the use of a digital hologram. This allows us to achieve complex bubble configurations. A single bubble can be sufficiently well modeled with an inviscid liquid using a potential flow; this model suffices for the description of single acoustic driven bubbles, too.

We demonstrate that coalescence of two bubbles expanding next to each other is occurring only in a narrow range of phases for the present experimental parameters. Patterns of four (not shown here), five, and nine bubbles demonstrate similar features: the central bubble possesses the longest lifetime, while the outer bubbles collapse with jet formation toward the central bubble. This collapse can be strongly affected by an external sound field leading to shorter and potentially stronger collapses.

This work serves as a step to study the enhancement of cavitation cluster collapses through an external driving while having precise control over the position and timing of the bubble generation. Future work may focus on enhanced light and sound emission from forced cluster collapses and an extension of the bubble cluster dynamics to three-dimensional geometries.

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