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High Speed Visualization of Acoustic Cavitation Bubble Dynamics near a Rigid Surface

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Summary

The presented concept involves high-speed video imaging of the bubbles generated due to acoustic cavitation. A gaseous bubble excited using ultrasonic waves oscillates at the exciting frequency and can undergo different types of oscillations, viz. stable or transient. In stable cavitation the oscillations last for multiple cycles before the bubble collapses. The bubbles undergoing transient cavitation, on the other hand, expand within couple of cycles and explode violently. The dynamics of the bubbles near a rigid surface shall be investigated using a high-speed camera with a frame rate of 1 million frames/s. The visualizations have been performed in the standing wave field of a 75 kHz transducer. A long distance microscope (W.D = 23.5 mm) consisting of infinity corrected objective has been used with the camera. The time scales of bubble oscillations are so short that a powerful light source is necessary for reasonable illumination. A super pressure short arc mercury lamp (200 W) light source fitted with a 320 nm – 700 nm filter is used for illumination. This light source is coupled to a liquid light guide and a collimating lens. The polished bottom surface of a stainless steel rod is chosen for the observation of cavitation activity. The water level is selected such that standing waves are formed in the system. The rod is placed at a location such that the cavitation bubbles are observed on the surface. Similarly a hydrophone is used in order to measure the sound pressure level and record the frequency spectrum for better understanding of bubble dynamics. In the current study the nature of acoustic cavitation bubbles generated and driven using ultrasound near a rigid surface is investigated in terms of number of bubbles, bubble size distribution and their relation to the incoming pressure wave.

Introduction

Acoustic cavitation is a physical phenomenon which involves the formation of cavities in a liquid when a sound wave imposes a time-varying sinusoidal pressure on the steady ambient pressure. A liquid contains pre-existing nucleation sites where gas or vapor may be trapped. As a result of reduced pressure during the negative part of the cycle, these gas pockets grow and subsequently detach to form so called "cavitation" bubbles. Under the influence of an external sound field, these bubbles can grow either into "stable" bubbles which oscillate nonlinearly around an equilibrium radius for many cycles or “transient” bubbles which expand to many times their original size within one pressure cycle and collapse violently. This peculiar nature of cavitation bubbles gives rise to interesting phenomena such as sonochemistry, acoustic microstreaming, molecular degradation, erosion, etc.

The surface erosion caused by cavitation bubbles has been a subject of interest for quite long time now, dating back to the end of 19th Century. The prime concern then was to understand the damage caused to the marine propeller blades which rendered them useless within a short time span. Lord Rayleigh 1917 developed a theory about the implosion mechanism of spherical cavities in a liquid which creates extremely high pressures in the concluding stages. Being a highly dynamic process with very short time scales, the investigation of acoustic cavitation requires high-speed visualization techniques. Benjamin et al. 1966, Chahine 1982, Chahine 1984, Blake et al. 1987 used high speed visualization to study the growth and collapse of cavities created by a kinetic impulse. Olson et al. 1969 generated the bubbles using ultrasound horn, whereas Lauterborn 1976, Mettin et al. 1999, Brujan 2000 focused on the dynamics of laser induced bubbles using high speed photography. Koch et al. 2003 used high speed imaging techniques to investigate bubble interaction and cluster formation at and near a solid surface in an ultrasound standing wave at 40 kHz. Bai et al. 2008 made a high-speed photography study of the collapse and rebound of bubbles produced by an acoustic horn at 20 kHz. Thus it is evident that majority of the studies reported in the literature related to the investigation of cavitation activity near a solid surface rely on the generation of cavitation bubbles using either the kinetic impulse, laser or electric discharge. Moreover, major emphasis has been laid to the understanding of bubble collapse. Not much information is available about the nature of cavitation bubbles produced on a rigid surface within the pressure field of an ultrasound transducer.

In the present study we are concerned with the high speed visualization of cavitation bubbles created using an ultrasound transducer in water in the proximity of a rigid boundary. The visualizations have been performed in the standing wave field of a 80 kHz transducer. The following sections describe the experimental setup, results, and discussions followed by conclusions.

Experimental Setup

The schematic diagram of the experimental setup used in the current study is shown in Figure 1. A function generator and power amplifier module (Weber Ultrasonics GmbH, SONICDIGITAL MG PREMIUM) is used to generate a sinusoidal signal which is fed to the cylindrical piezoelectric element (Weber Ultrasonics GmbH) having a resonance frequency of 75 kHz. The piezo transducer (Ø =25mm) is glued to a 1.5 mm thin Stainless Steel membrane. This membrane, in turn, is connected to a cylindrical Plexiglas® setup. The apparatus is kept sealed using an O-ring. The pressure in the cylindrical chamber is recorded using a hydrophone (Reson A/S TC-4038) connected to a voltage preamplifier. The hydrophone signals are fed to a data acquisition system (NI-DAQ USB 6259). Similarly, a voltage signal is extracted from the signal generator for comparison.

The visualization experiments are carried out using a high speed IS-CCD camera (Shimadzu Corporation, HPV-2) capable of 1 Million fps with a resolution of 312 X 260. This high speed implies that the time for which the shutter is open can be as short as 1µs. The camera captures a sequence of 101 frames. A long distance microscope (W.D = 23.5 mm) consisting of infinity corrected objective (Mitutoyo Plan Apo 20X), infinity corrected zoom lens (Navitar, Inc., Ultrazoom 6.5X) and F-Mount adapter tube (Navitar, Inc.) is used with the camera. Such short time scales require extremely powerful light source for reasonable illumination. A super pressure short arc mercury lamp (200 W) light source fitted with a 320 nm – 700 nm filter is used for illumination. This light source is coupled to a liquid light guide and a collimating lens. The polished bottom surface of a stainless steel rod is chosen for the observation of cavitation activity. The camera, light source, hydrophone and the oscilloscope are triggered simultaneously. This enables us to relate the images to the acoustic pressure amplitude in the water column at that instant.

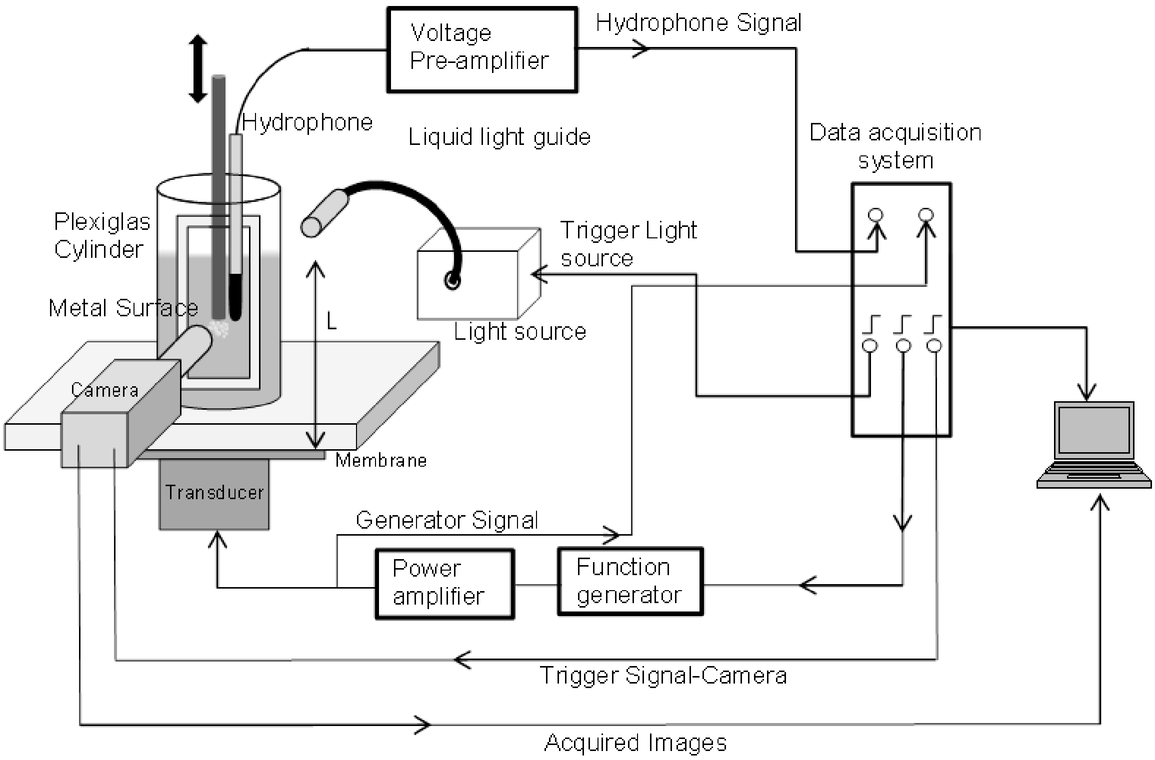

Fig. 1 Sketch of the experimental setup

For each measurement, non-sterile ultrapure water (Biochrom AG) kept at 20°C is used. The water column is filled up to height $L = (2n+1)\lambda/4$ (35-40mm), in order to generate a standing wave in the setup and the incoming acoustic wave amplitude is 30W. The onset of standing wave is marked by the oscillating motion of the air-water interface and sudden increase in the pressure amplitude shown by the hydrophone. The ultrasound transducer is now switched on and the camera, light source, hydrophone and the oscilloscope are triggered simultaneously. In order to avoid the influence of hydrophone on the pressure field right next to the metal rod, it is placed away from the metal rod. Moreover it is observed that the presence of hydrophone next to the metal surface has an influence on the cavitation activity near the surface.

Results and discussions

Owing to the highly unpredictable nature of acoustic cavitation, large amount of measurement have been carried out in order to extract sufficient statistical information about the bubble dynamics. The videos have been analyzed using the image processing tools available in Matlab®. The aim is to detect the bubbles and follow their growth characteristics and abundance. The problem faced during image processing is the uneven background illumination which arises due to the shadowing effect of large bubbles. The bubbles which are present in the path of illumination but not in the focal plane of the lens tend to scatter the light falling on the bubbles in the focal plane. This leads to a dark background. On the contrary when very less bubbles are present in the scene then the illumination is too bright. Hence proper image intensity thresholding helps to reduce the problem of uneven illumination. The thresholding is followed by segmentation and feature extraction. Once the region of interest has been selected, it is further processed by Hough Transformation (Duda et al. 1972) for the detection of circular edges. The Matlab® code by Peng 2005 has been used to carry out Hough transformation

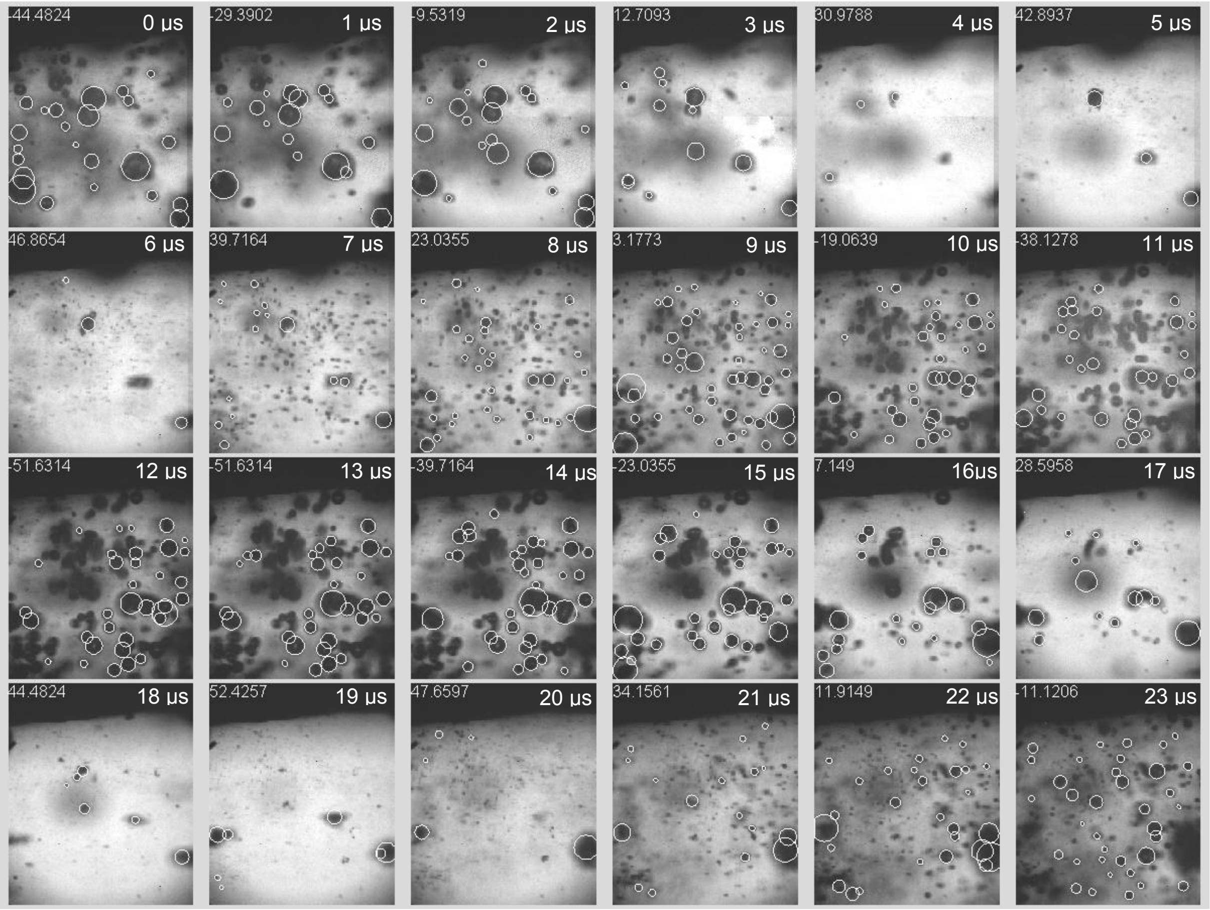

Fig. 2 Image sequence for 23µs at 30 W with pressure information

Figure 2 shows the result of image processing in an image sequence at ultrasound 30W pressure amplitude. The time difference between two successive images is 1µs. The applied scheme has been successful in detecting the location of the bubbles and their corresponding radii. The numbers on the top left end of each picture correspond to the acoustic pressure in the column at that instant. Image processing is severely hampered due to the lack of contrast and sharpness in the given pictures. Apart from that the Hough transform algorithm detects many pseudo circles which need to be filtered out. As shown in the figure, the white circles envelop the bubbles and the radius of the bubbles can thus be determined.

It is known that during the negative pressure cycle, the size of the bubble increases due to the rectified diffusion (Hsieh et al. 1961). From Fig. 3 it can be seen that the size and the number of the bubbles created due to acoustic is dependent on the acoustic pressure in the system. During the negative pressure cycles the number of generated bubbles is much higher than that during the positive pressure cycle.

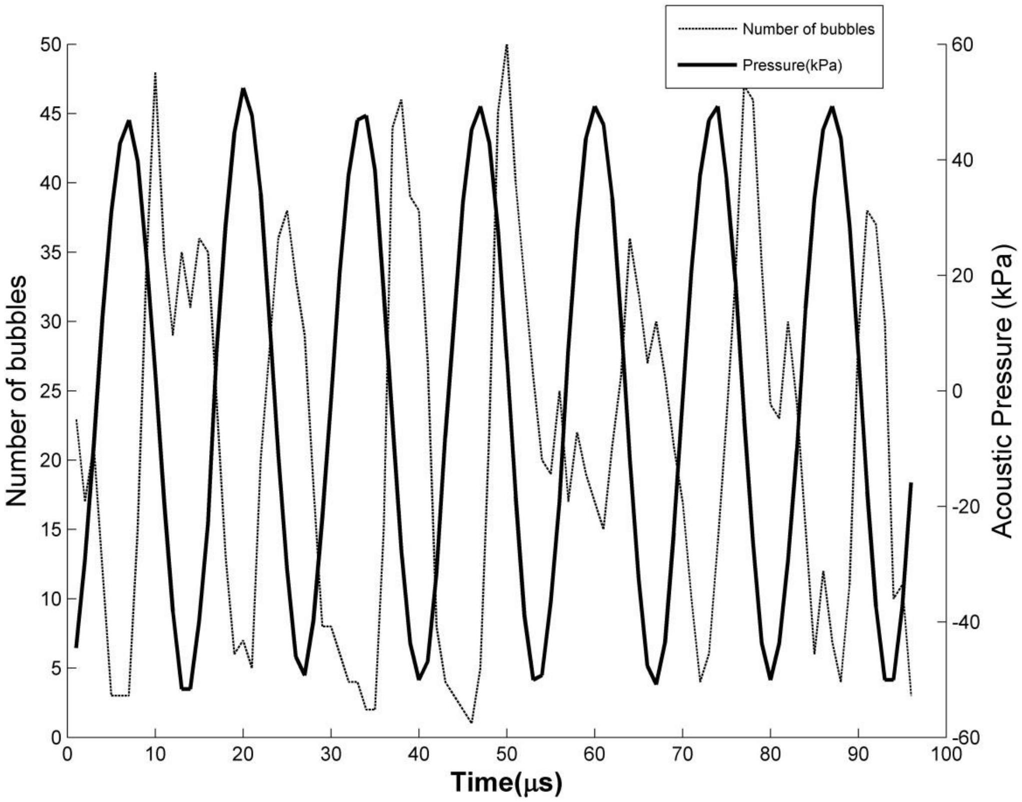

Fig. 3 Dependence of the number of bubbles generated on the acoustic pressure measured by the hydrophone in the frame sequence in Fig.2

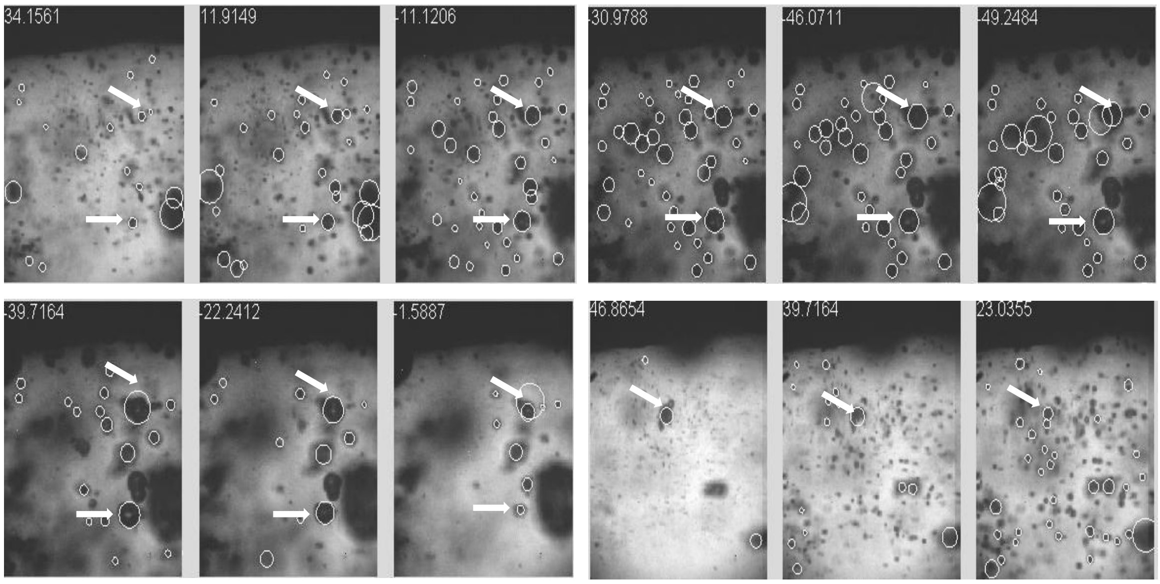

Fig. 4(a) Images frames under consideration (21 μs - 32 μs)

Figure 4(a) shows the image frames under consideration for the study of the dependence of bubble radius with the acoustic pressure. The two bubbles considered here are shown by a horizontal and an inclined arrow respectively. The growth curves of these two bubbles are shown in Fig 4(c) and 4(d) respectively. The corresponding pressure wave is shown in Fig

4(b). It can be seen that as the bubble size increases as the negative pressure increases and decreases as the pressure increases.

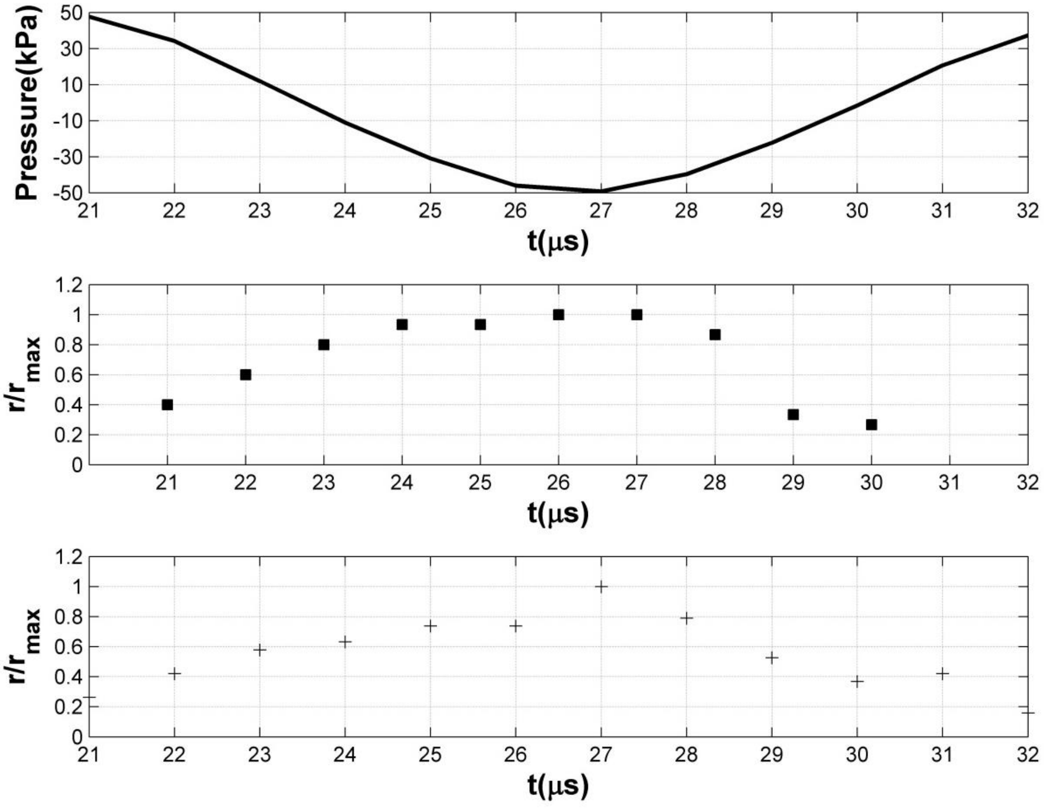

Fig. 4(b): Acoustic pressure in the water channel. 4(c): Growth curve of the bubble shown by the horizontal arrow. 4(d): Growth curve of the bubble shown by the inclined arrow

Conclusion

This study has shown the nature of dynamics of oscillations of acoustic cavitation bubbles in water near a rigid surface. It can be concluded that as the bubble population is a function of the incoming acoustic pressure wave. The bubble population increases during the negative phase of the pressure cycle and decreases again during the positive part of the cycle. In addition the individual bubbles oscillate as expected. They grow during the negative part of the pressure cycle. In order to understand the unpredictable nature of oscillating bubbles, it is of utmost importance to develop robust image processing techniques dedicated to this cause and analyze large amount of data in order to develop the statistics. This information can come handy for the optimization of various applications utilizing acoustic cavitation.

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