On Fiber Optic Probe Hydrophone Measurements in a Cavitating Liquid (L)

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(Dated: June 29, 2007)

The measurement of high-pressure signals is often hampered by cavitation activity. The usage of a fiber optic probe hydrophone is becoming the gold standard to measure in this harsh environment. Yet, when measuring in a cavitating liquid large variations in the signal amplitude are found, in particular when the pressure signal recovers back to positive values. Here, we photograph with shadowgraphy the wave propagation and cavity dynamics and reveal the importance of secondary shock-waves emitted from collapsing cavitation bubbles. Interestingly, just adding a small amount of acidic acid reduces the cavitation activity to large extend. With this treatment we find an altered primary pressure profile which does not force the cavitation bubbles close to fiber tip into collapse. Thereby, the shot-shot variations are greatly reduced.

I. INTRODUCTION

Accurately registering the wave shapes in medical applications such as in shock wave lithotripsy (SWL)[1], shock wave therapy (SWT)[3], histotripsy[4], or high intensity focused ultrasound (HIFU)[5] is of prime importance for quality assurance of therapeutical devices. Pressure measurements of high-pressure finite amplitude and shock-waves are not only demanding because of the high frequencies involved. The recording of negative pressures is also challenging because the sensor has to withstand cavitation[6]. In general cavitation can occur when the pressure drops below the vapor pressure while nuclei[7] are present which explode into vaporous cavities. When the pressure recovers again the cavities implode thereby focusing destructive energy from the liquid onto very small scales. When the sensor is too close to the collapsing cavity it can easily be damaged. Yet, even if the sensor withstands the cavity collapse measurements of the pressure are often hampered because of the need to distinguish whether the sensor is entrained within a cavity or accurately registering the liquid.

A device which operates in this demanding environment is the fiber optic probe hydrophone developed by Staudenrauss and Eisenmenger (1992)[8]. In this device laser light is coupled into a glass fiber. At the fiber tip the light is reflected; the intensity of the reflected light is a function of the jump in the index of refraction from glass to water. The index of refraction is related through the well known Gladstone-Dale relationship to the pressure[9]. Thus, the pressure can be determined from the intensity reflected back into the fiber[10] and registered with a sensitive photodetektor. This type of hydrophones are mentioned in the IEC guidelines for quality assurance of lithotripters to measure at the focus[?] because it several unique advantages compared to the other hydrophones: (i) The strong adhesion of water on the glass reduces nucleation of cavitaties on the sensor, (ii) when the fiber tip is broken the fiber can easily be re-cleaved and cut, (iii) the entrainment of the fiber into a cavity leads to an instantaneous jump in the signal thus entrainment of the sensor is easily detectable, (iv) and due to the well documented Gladstone-Dale relationship calibration is a simple task.

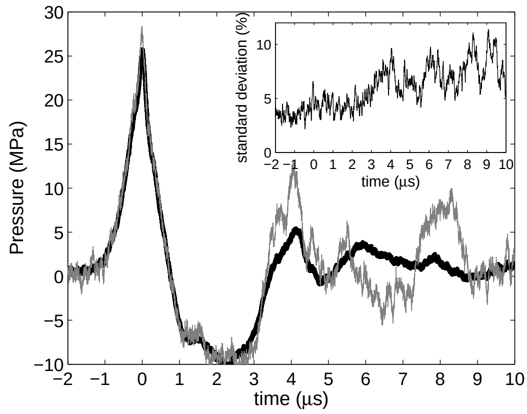

FIG. 1. Pressure signals recorded with a FOPH device in degassed Millipore water. An averaged signal (thick line) and a randomly selected single recording (thin line) are compared. The inset depicts the standard deviation (SD) of the signal as a function of time. Interestingly the SD increases at time $t = 3.2\,\mu$s that is when the pressure recovers.

Yet, there exist some difficulties with interpreting the signals. When studying waves with a steep pressure rise which are trailed by a negative pressure cycle very strong shot-to-shot variations occur at the moment when the

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negative pressure recovers. Averaging the signal over multiple events removes these oscillations but leaves the experimenter with some discomfort on how to interpret the data. An example of the signal which is achieved by this averaging procedure is depicted in Fig. 1 (thick line). The measurements were done in partially degassed Millipore (Milli-Q synthesis A10) water. The effect of cavitation on the wave propagation has been reported by Pishchalnikov *et al.*[11]. They find a shortening of the tensile wave and explain it with the loss of energy from the tensile wave which growss cavition bubbles in the liquid. In recent simulations by Liebler *et al.*[12] coupling the non-linear wave equation model with in effective medium which described the gas phase it was revealed that the wave form can be greatly altered. Not only the tensile phase is shortened (as reported in Ref[11]) but also a second pressure increase following the shortened tensile phase is found in the simulations and experimentally. The altered waveform which has also been reported by Arora et al.[14] is explained by Liebler *et al.*[12] modifying especially the diffracted waves from the transducer edge.

The averaged waveform over 18 pressure signals presented in Fig. 1 is compared with a randomly chosen recording from this set (thin line in Fig. 1). The variations between the single and the averaged signal remain small during the initial pressure rise to 26 MPa and drop to -10 MPa. This initial variability can be explained with the noise of the laser source and measurement noise of the photodetector. However, at time $t = 3\,\mu$s -that is when the pressure recovers- clear differences appear. They are detailed in the inset of Fig. 1 by plotting the standard deviation of the signal. Up to approximately $t = 3\,\mu$s the standard deviation stays constant and is caused by the inherent noise, but it increases when the pressure recovers.

What causes the loss of reproducibility in the data? Candidates are cavitation bubbles emitting pressure waves, yet we can't exclude cavitation occurring on the glass fiber which might affect the light transmission in the glass fiber and has been suggested in Ref.[11].

In the work of Liebler[12], it was reported that the pressure signal is affected by adding small amounts of a mild acid acetic acid. Their explanation was: cavitation is reduced by chemically dissolving calcite particles which serve as cavitation nuclei in the water, a hypothesis put forward bye Eisenmenger[13].

These important findings are now put under a visual test. High-speed photography of the interaction of the wave with a fiber optic sensor is conducted to document the effect of cavitation on the glass fiber sensor. First we describe the experimental set-up which allows to conduct this task and visualize the interaction of the pressure-wave with the glass fiber tip.

a. Experimental setup The pressure waves are generated with a piezoelectric device used for shock wave therapy (Piezolith 100, Richard Wolf GmbH, Knittlingen, Germany)[?] . The pressure measurements are done with the fiber optic hydrophone (FOPH 500, RP Acoustics, Stuttgart, Germany) which is positioned in the focus with a motorized three axis translation stage. The shock wave and the cavitation dynamics are visualized with a shadowgraphy technique using stroboscopic illumination (Fig. 2). The image of the shock wave and the cavition bubbles are illuminated with a frequency doubled Nd:YAG laser pulse of 7 ns duration (Solo PIV, New Wave Research, wavelength 532 nm) fed into a fluorescent cell filled with an ethanol-dye mixture (0.417 mg/ml, LDS 698, Exciton Inc., Dayton, U.S.) and then coupled into a glass fiber to the shock wave generator located on a second table. The fluorescent light allows for speckle free illumination. The light escapes the other fiber end and then becomes slightly diffused with a tissue paper. The images are taken with a CCD camera (Imager 3S, LaVision, Goettingen, Germany) which is equipped with a long distance microscope (K2, Infinity, U.S.) and a CF3 objective. The optical resolution is 1.52 μm/pixel. The timing unit (BNC 555, Berkeley Nucleonics, CA, U.S.) which is triggered through an induction coil connected to the shock wave generator fires the laser at variable delays with respect to the shock wave. The travel time of the wave from the transducer to the acoustic focus where the fiber optic probe hydrophone is located is approximately 50 μs.

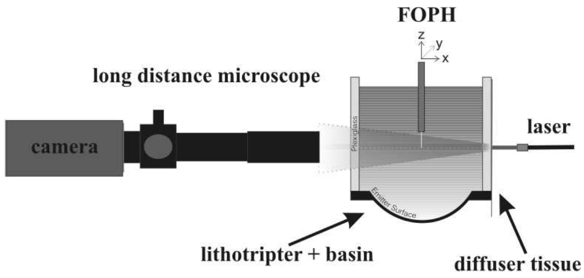

FIG. 2. Experimental setup used both for pressure measurements as for shadowgraphy imaging.

A stroboscopic picture sequence from the plain water experiment is shown in Fig. 3 and they are conducted in the same setup as the recording of the pressure signals shown in Fig. 1. The first frame displays the wave shortly after it passed over the glass fiber tip. The time $t = 0$ is defined when it just meets with the glass fiber tip. A shadowgraphy technique is sensible to the second derivative of the index of refraction[16]. Thus, the structure depicted in stop-motion in Fig. 1 is the image of the pressure maximum of the wave, see $t = 0$ in Fig. 1. At $t = 1.4\,\mu$s cavitation bubbles appear in the liquid. Spherical pressure waves appear shortly after, and reach about the position of the fiber tip in the fourth frame, $t = 3.0\,\mu$s. This correlates with the start of the signal deviations in the pressure recordings. The spherical waves are created from collapsing cavitation bubbles. Presumably, the second pressure increase following the tensile

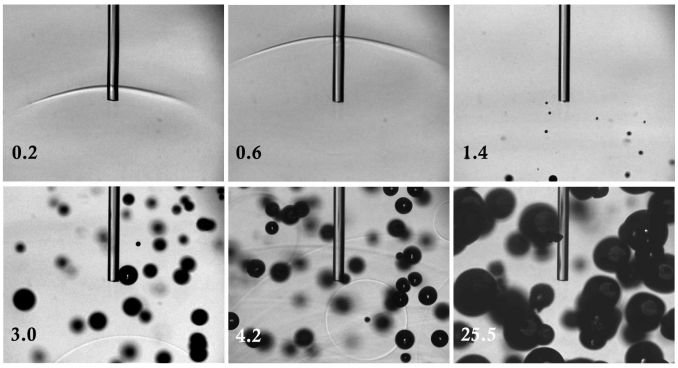

FIG. 3. Flash photography of the shock wave passage and following cavitation activity at the tip of the FOPH. The time in the individual frames is given relative to the shock wave impact on the the glass fiber tip. Please note, the spherical shock waves in frames 4 and 5.

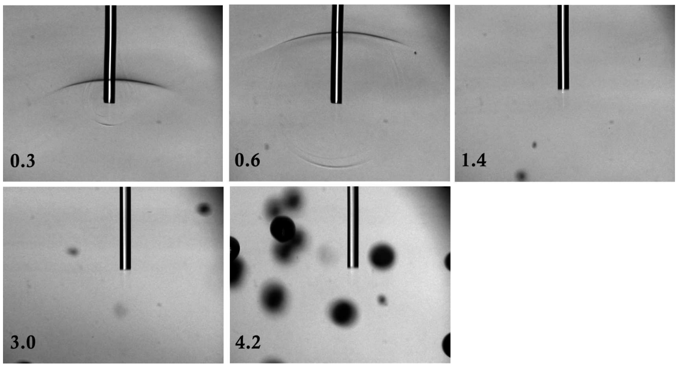

FIG. 4. Flash photography of the shock wave passage and following cavitation activity at the tip of the FOPH in a water-acid solution (4 % vol actetic acid). The individual times stated in the are with respect to figures are 0.2, 0.6, 1.4, 3.0, 4.2, and 25.5 μs after the shock wave impact on the fiber tip.

phase causes the shrinkage of the bubbles. The origin of the pressure increase is a diffraction effect as is supported by the simulations of Liebler et al.[12].

Let's now have a look on the cavity dynamics after the acetic acid (4 vol %) has been added to the water. This concentration was chosen because Liebler et al.[12] observed excellent agreement of a bubble-free simulation and FOPH measurements. It was suggested, that cavitation activty is suppressed and the wave is not altered by the interaction with bubbles. Figure 4 depicts the shadowgraphy sequence in the solution with acetic acid. In the first two frames the primary wave and also the reflected wave from the tip of the fiber is visualized. The initial pressure wave form is hardly altered as compared to the water case. The first cavities appear at $t = 1.4\,\mu$s but only two, a tenth of the number of bubbles from the plain water case. A second difference is that at later times we don't find spherical waves emitted from collapsing cavitation bubbles. This is interesting, because a few

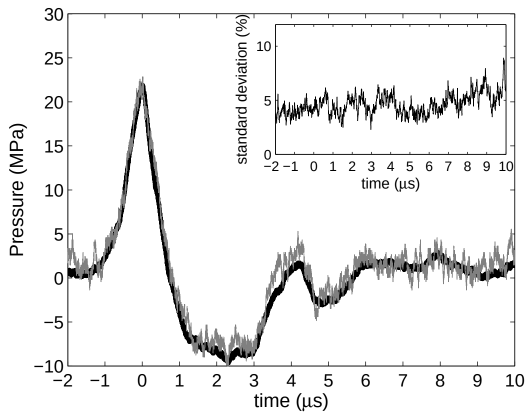

FIG. 5. Pressure signals recorded with a FOPH device in degassed Millipore water with *4 % vol. acetic acid*. An averaged signal (thick line) and a randomly selected single recording (thin line) are compared. The inset depicts the standard deviation (SD) of the signal as a function of time. Here, SD stays constant for the measured time.

bubbles are nucleated in the field of view and thus might qualify for a forced collapse. The addition of acid to the liquid causes a strong reduction on the number of bubbles. But it also causes a second effect, it changes the time averaged pressure recordings. We find in the plain water case a second overpressure peak after the pressure recovered from the negative pressure, $t = 4.1\,\mu$s in Fig. 1 which is absent here, very similar to the finding of Liebler et al.[12]. Presumably, as the medium contains less bubbles the diffracted waves from the transducer edge are less effected. Thus do not give rise to the overpressure. Therefore, the remaining cavities are not compressed and do not give cause secondary shock waves. Thus, the signal becomes much more reproducible. The last finding is strengthened by the plot of the standard deviation in Fig. 5. It stays constant over the measured time.

In summary, pressure measurements in a cavitation liquid are a superposition of the pressure induced by the direct wave and that from secondary waves emitted by collapsing bubbles. The variability of the signal from shot-to-shot is caused by the forced collapse of cavities close to the fiber tip. Yet, the direct wave can be strongly altered by the cavitation it creates on its way to the to the measurement region.

This work has been funded through the VIDI grant from NWO (The Netherlands).

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