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Adaptive Visualization for Cavitation and Shock Waves Phenomena

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Abstract: We present a highly adaptable system to visualize a combination of slow and fast phenomena in transparent media simultaneously. Various images and video examples are acquired, portraying the response of water to optical breakdown in the vicinity of different boundaries. The light source is a laser diode module coupled to a standard multimode fiber that emits light in the near infrared wavelength region. The examples include single-frame visualization of shock wave propagation or bubble dynamics, videos of secondary cavitation generation by the refocused shock wave reflected from a concave boundary and interaction of shock waves with solids of different acoustic impedance. The illumination system is synchronized with the excitation laser and the still or the high-speed camera. It is intended to be used as a light source for high-speed movie shadowgraphy, schlieren photography/cinematography, background-oriented schlieren (BOS) technique, and high-speed photo-elasticity. It offers a unique way of studying shock waves and their interplay with cavitation bubbles in transparent media or other high-speed phenomena, such as transient pressure fields, that affect its density. We foresee that the presented illumination system will be well received also in the studies of laser shock processing, cavitation erosion, and medicine.

Keywords: high-speed photography; laser diode; pulsed illumination; cavitation; shock waves

1. Introduction

We have developed an adaptive illumination system to visualize at once a combination of slow and fast phenomena in transparent media [1]. What is meant by slow/fast is that slow phenomena are those where sharp images are obtained during the exposure time of a single frame, while changes are observed between the frames. The fast phenomena would be motion-blurred on the sensor during frame exposure and thus demand a short intra-exposure probing pulse to freeze the object plane onto the sensor before the image of the object moves laterally more than 1 pixel. The slower phenomena are visualized frame-by-frame, similar to the conventional continuous illumination or single-pulse-per-frame illumination techniques, while faster phenomena are captured within each frame by using multiple probing pulses that freeze the rapid motion of the propagating object at different locations on the sensor.

An illustrative example that calls for such an illumination system is the qualitative visualization of phenomena following a laser-induced breakdown (LIB) in liquids [2]. Such a breakdown is accompanied by an interesting interplay of cavitation structures and the emission of shock waves [3]. As for the speed at which optical changes are expected, the cavities can be considered as structures with a slow dynamic character, while shock waves can be assigned a fast character [4].

This illumination system can be used in connection with single-shot or high-speed video cameras and is intended to be used as a highly adaptable light source for high-speed movie shadowgraphy, schlieren photography/cinematography [5], a background-oriented schlieren (BOS) technique [6] and high-speed photo-elasticity [7].

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2. Materials and Methods

The presented high-speed photography setup is schematically depicted in Figure 1. The adaptive illumination system is built from a laser diode and a custom high-speed electronics driver based on a computer-controlled field-programmable gate array (FPGA) module that produces pulses as short as 16 ns covering the whole bandwidth of repetition rates from single shot to approximately 30 MHz. The duration of the illumination pulses and the timing can be set from pulse to pulse through the computer interface. The control electronics can be synchronized with an arbitrary external trigger. The light source is a commercially available single-emitter laser diode module coupled to a standard multimode 125 μm fiber that emits light at a nominal wavelength of 793 nm. This wavelength offers a very good trade-off between power, brightness, camera-sensor sensitivity, and the transmissivity of water. Due to the fiber-based architecture, power scaling can be easily realized, which further ads to the flexibility of the system and its capability to adapt to different requirements for high-speed photography. The illumination system allows for synchronization with the excitation laser and the still camera for the multi-illumination, single-frame (MI:SF) approach or directly with the output sync signal from a high-speed camera for a multi-illumination, multiframe (MI:MF) approach.

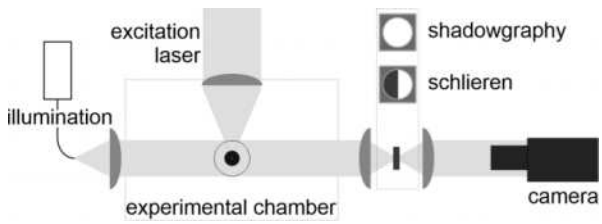

Figure 1. Experimental setup for generating and visualizing laser-breakdown-induced cavitation bubbles (the black disk) and shock waves (the circle surrounding the bubble).

The illumination system was applied to the optical setup for shadowgraphy, which is easily convertible to the schlieren setup for enhanced shock-wave photography by spatial filtering using a knife edge. To induce an optical breakdown, a Q-switched Nd:YAG laser was used to generate 6-ns pulses (FWHM) with an energy of 10 mJ that were focused into the experimental chamber filled with distilled water.

3. Results

The performance of the presented illumination system is best demonstrated by illustrative visualizations of the shock waves and cavitation bubbles.

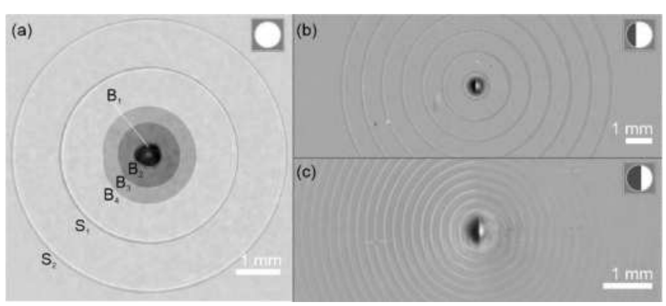

Figure 2. Initial growth of a LIB-induced cavitation bubble in water and shock-wave emission illuminated with multiple visualization pulses using the MI:SF approach. (a) Four probe pulses at 1.25 μs, 2.0 μs, 17.0 μs, and 54.5 μs after LIB using an empty aperture. (b) Seven probe pulses spaced by 500 ns using a weakly closed aperture. (c) Twenty probe pulses spaced by 125 ns using a strongly closed aperture.

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Figure 2(a) presents the growth of the laser-induced cavitation bubble and the emission of the shock wave in water. The shadowgram was acquired using the MI:SF approach upon the removal of the knife from the aperture. The shock waves are labeled with $S_\#$ and the boundaries of the cavitation bubbles with $B_\#$, where # stands for the number of the consecutive pulse. Four 16-ns pulses at a peak power of 8 W, launched 1.25 μs, 2.0 μs, 17.0 μs, and 54.5 μs after the breakdown, outline the boundary between the gaseous bubble interior and the surrounding liquid. The first two pulses also capture the spherically propagating shock wave. Except at the very center, the bubble deflects the probing light and thus appears black. The integrated light level of all four pulses is close to the saturation level of the camera, which means the bubble frozen by the first pulse appears black, while its increments between subsequent pulses are seen discretely brighter, giving a clear impression of the bubble's growth. A similar LIB event was visualized in Figure 2(b), except that this time 7 pulses with 500-ns spacing and a smaller energy were used for discretized illumination with a weakly closed aperture. In Figure 2(c) 20 pulses were used with 125-ns interpulse delay and a strongly closed aperture. Allowing for adequate background illumination, the more the knife edge cuts the focus, the better the shock-wave contrast

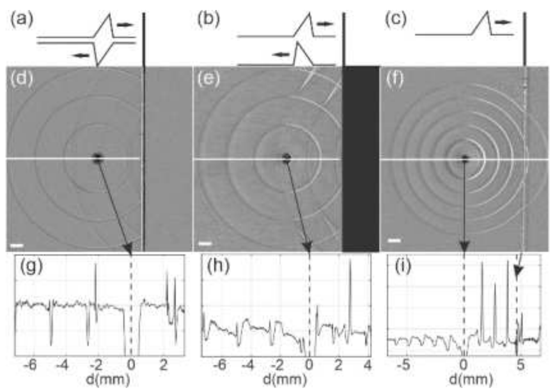

Figure 3. Reflection of water-born shock wave from media with various acoustic impedances. (a,d,g) free-water interface in vertical orientation (phase reversal at reflection), (b,e,h) aluminum plate (no phase reversal), and (c,f,i) PMP plate (no reflection). (d-f) Schlieren photographs in the MI:SF approach with the vertical knife filtering were illuminated with a triple (d,e) and a quintuple (f) train of probe pulses. White bar: 1 mm.

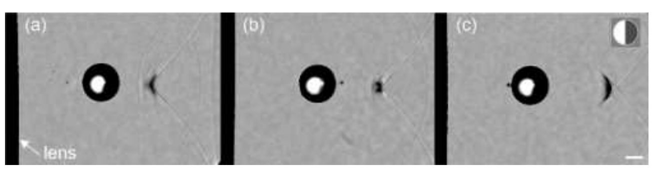

Figure 4. Shock wave focusing. (a) Shock wave converging towards the acoustic focus, (b) at the acoustic focus and (c) diverging from the acoustic focus after passing it.

In Figure 3, the shock wave was sent to be reflected from the plane targets of different acoustic impedances, such that the shock wave is reflected by changing the polarity [Figures 3(a,d,g), free-surface of water, subfigure rotated by 90°], without changing the phase [Figures 3(b,e,h), aluminium], or with no reflection [Figures 3(c,f,i), water impedance-matched transparent polymethylpentene (PMP)]. The transmission of the shock wave into the solid PMP, where it propagates faster, can also be observed in the right-most part of Figure 3(f), demonstrating the ability of the visualization system to also capture shock waves in transparent solids. Figures 3(g-i) depict the pixel level profile along the white line marked in Figures 3(d-f).

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An example of a shock-wave focusing is captured in Figure 4 using the MI:SF approach. A portion of this LIB-generated transient was reflected from a solid, concave acoustic mirror (also acting as a focusing optical lens for the laser pulse) and refocused on the axis after first being scattered by the cavity. The acoustic focus can be easily located by identifying the shock wave front before [Figure 4(a)], in [Figure 4(b)] and after [Figure 4(c)] the acoustic focus.

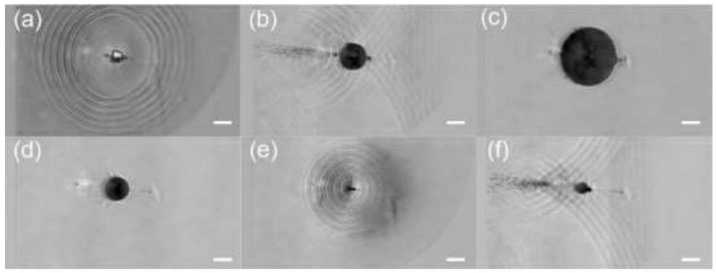

Figure 5. (a-f) Selected frames from the high-speed schlieren video providing a visual insight into the bubble and shock-wave dynamics after a LIB in water near a concave acoustic mirror. The video was acquired with a framerate of 100 kfps using the MI:MF approach. White bar: 1 mm.

Further versatility of the illumination system is demonstrated with a MI:MF video approach, where slow phenomena are followed frame-by-frame, while fast phenomena are frozen multiple times within each frame. The experimental configuration to obtain Figure 5 is the same as in Figure 4. Figure 5 presents six selected frames from the high-speed schlieren cinematography with a framerate of 100 kfps using a train of six illumination pulses per frame with an intraframe separation of 250 ns. Watching such a video gives information about the evolution of cavitation structures, while inspecting each frame separately, clearly illustrates the propagation of shock waves.

In conclusion, the demonstrated high-speed multi-illumination of a single photograph or multiple video frames offers a unique way of studying shock waves and their interplay with cavitation structures in transparent media or other high-speed phenomena that affect its density. We foresee that the presented visualization technique will be well received also in the studies of laser shock processing, cavitation erosion and cell transfection.

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