Ultrafast measurement of laser induced shockwaves

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Background – During laser induced breakdown, shock waves are generated. The rise time of shock waves in solids and glycerol was studied before, however, their time resolution was insufficient for measurements in water [1].

Our single mode fiber optic hydrophone is uniquely suitable for such fast measurements. The measurements were performed in distilled water (~0.7 cst, R > 1 MΩ) as well as in oil (5 and 50 cst, Sigma Aldrich). In addition, shockwave rise time dependence on the distance from the centre of the laser induced breakdown for extremely small distances was measured.

Methods – Single pulses of a 60 ps, 1030 nm laser, having energies from 1.5 µJ to 7.5 µJ were used to initiate breakdown in experiments. The breakdown threshold (50% probability of breakdown) is 1.1 µJ.

A custom made fiber optic probe hydrophone (FOPH) was used to measure the shock wave pressure. Single mode fiber with 5 µm core and 125 µm cladding was used. The very small dimension of the sensing area (5 µm) results in a very fast and spatially almost point-like detection as described in [2]. The shockwave pressure changes the refractive index of water or oil, which in turn changes the optical reflectance at the fiber tip – the measured quantity. For both water and oil the reflectance decreases with pressure.

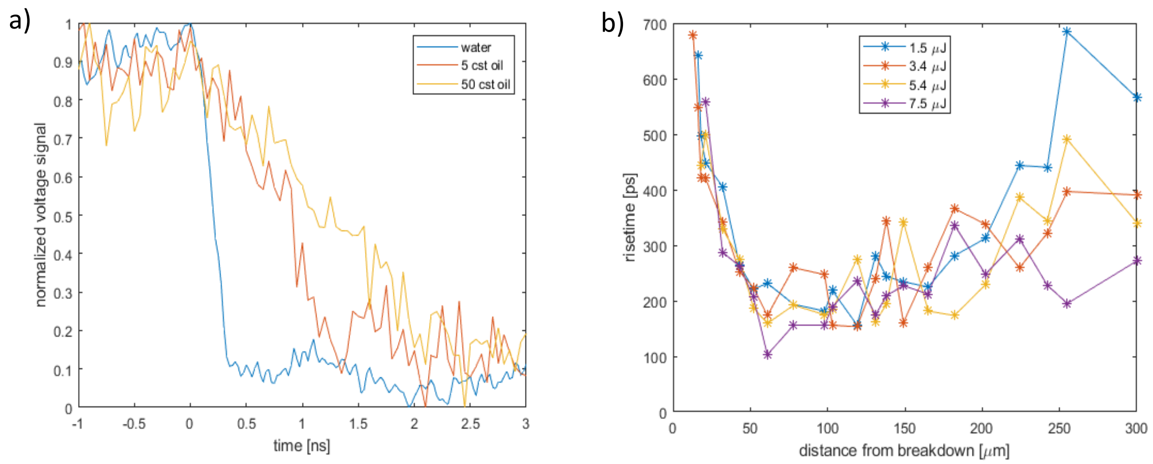

Figure 1: a) Shock wave traces in water and oil. The arrival of the wave is at t=0. The 20-80% shockwave pressure rise times in water, 5 cst and 50 cst oil are measured to be 180 ps, 500 ps and 1100 ps, respectively; and approximately twice as much for 0-100% pressure change. **b)** Shock wave rise time measured in water at very small distances form the source for various laser pulse energies. Shortest rise times of approximately 150 ps are observed for distances from 60-100 µm.

Results – The laser induced breakdown at 3.4 µJ pulse energy produces a shock wave, which is measured at a distance of approximately 80 µm from the breakdown for all three liquids (Fig. 1 a). The shock wave in water is measured to have a rise time of 180 ps between 20% and 80% of the pressure (equivalently – change between 80% and 20% of the voltage). This short rise time is significantly sharper compared to rise times in 5 cst and 50 cst oils (500 ps and 1100 ps, respectively). This observation is in agreement with theoretical predictions [3] and with previous studies in glycerol and solids that also showed smaller rise time for lower viscosity materials. Shock wave rise time trends are significantly slower than linear, with a factor of 6 change in rise time corresponding to the factor of 70 change in viscosity.

In addition, we analyse the rise time variation with the breakdown distance and breakdown energy in water. There are two observable trends – the rapid rise time decrease with distance in the first 50 μm from the breakdown, and the gradual rise time increase with increasing distance beyond approximately 150 μm. We believe that the main reason for the first trend is the fact that at such small distances, the shock wave is not yet fully developed [4] and the fact that at such small distances the contributions from different parts of the laser induced plasma arrive at the sensor at measurably different times. At distances of approximately 100 μm, the shock wave is already developed – all the partial contributions coalesce together to a single shock wave. Finally, at large distances, both the attenuation of shock waves due to propagation, as well as the decreasing pressure with distance, influence the resulting rise time. The comparison of these two reasons is difficult due to noise, however, it seems that the high frequency attenuation contributes to the rise time increase slightly more than the pressure decrease due to spherical spreading of the wave.

Conclusions – We have measured and analysed the rise times of the laser induced shock wave of lower viscosity fluids. The results suggest a similar trend as reported for solids and highly viscous glycerol. The extremely fast and small area measurements of the rise time very close to the source will provide the necessary data for the study and understanding of the shock wave formation and propagation in fluids.

References

[1] G.I. Kanel, A.S. Savinykh, G.V. Garkushin, A.V. Pavlenko, S.V. Razorenov, Shock Wave Rise Time and the Viscosity of Liquids and Solids, in Mechanics for Materials and Technologies, vol. 46, H. Altenbach, R. V. Goldstein, and E. Murashkin, Eds. Cham: Springer International Publishing (2017) pp. 257–263. doi: 10.1007/978-3-319-56050-2_13.

[2] J. Petelin, Z. Lokar, D. Horvat, R. Petkovsek, Localized Measurement of a Sub-Nanosecond Shockwave Pressure Rise Time, IEEE Trans. Ultrason., Ferroelect., Freq. Contr., 69:1 (2022) 369–376. doi: 10.1109/TUFFC.2021.3115629.

[3] I.B. Zelʹdovich, I.P. Raĭzer, Physics of shock waves and high-temperature hydrodynamic phenomena. Mineola, N.Y: Dover Publications (2002).

[4] M. Vassholz et al., “Pump-probe X-ray holographic imaging of laser-induced cavitation bubbles with femtosecond FEL pulses,” Nat Commun, vol. 12:1 (2021) pp. 3468 doi: 10.1038/s41467-021-23664-1.