Low-light imaging of structures in optically dense media

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Application Note

Introduction

In internal combustion engines, the injection of liquid fuel into the cylinder is one of the fundamental processes determining combustion efficiency. Today, one cardinal problem for engineers is the lack of physical understanding about the disintegration of the liquid fuel into an atomized spray. This process is located close to the injector nozzle and state-of-the-art imaging techniques suffer from combined low-scale structures and multiple photon scattering in this region. Images using monochromatic x-rays from a synchrotron[1] have shown that the spray core is not as dense as previously believed. Thus, recent research on imaging methods in this field strives for the suppression of diffusely scattered photons. Paciaroni and Linne[2] have proposed a shadowgraphy technique called "Ballistic Imaging": the basic idea for the suppression of diffusely scattered photons is to use the time delay scattered photons experience while propagating through the spray cloud due to multiple scattering events, see Fig.1. Therefore an ultrafast optical shutter based on the optical Kerr effect is employed, which is capable of shutter durations around 1 to 3 picoseconds. When the shutter is ideally synchronized, the first – "ballistic" – photons can pass the shutter and form the image while the late photons are blocked. This approach is also pursued at the Institute of Heat and Mass Transfer heading for a characterization of the spray-breakup of alternative fuels.

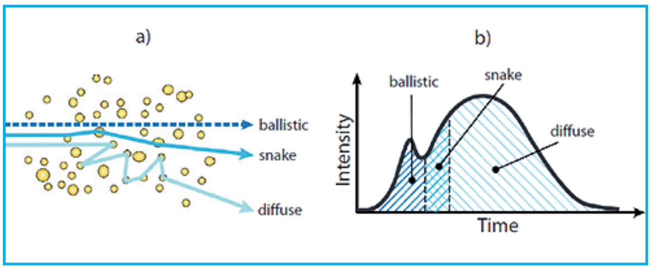

Figure 1: a) Theoretical classification of ballistic, snake and diffuse photons. b) Qualitative, temporal distribution of photons after passing the dense spray (compare Gord et al.[3])

One limitation of this approach is the amount of light that forms the image. The intensity of ballistic light can be several orders of magnitude less than the intensity of the diffuse light, which requires the utilization of a very sensitive camera capable of amplification of the low ballistic light intensity over the noise level.

Experimental setup

The light source of the experimental setup is an amplified Femtosecond-Laser producing light pulses of up to 25 mJ. One fraction of the initial pulse is used to switch the optical shutter, while the remaining light illuminates the object and is relayed through the Optical Kerr Shutter onto the sensor of the Andor EMCCD camera iXon+ DU888 EC-UVB.

In order to verify the working principle and analyze the specific influences on image contrast and quality, initial tests were carried out using a standard resolution target as object, see Fig. 2. The target is a reflective glass plate with transparent lines of different spatial frequency. The target is placed in a cell filled with a suspension of water and polystyrene particles. By varying the particle concentration various light attenuation factors can be realized.

Figure 2: Resolution Target in a glass cell filled with water (left) and Resolution target in a glass cell filled with a suspension of water and polystyrene particles (right)

Results

For the test case different particle concentrations were set up and images are compared for two cases: i) images taken with the Optical Kerr Shutter in place and optimum synchronization of the shutter and the illumination light (referred to as "gated" shadowgrams) and ii) images taken without the shutter in place (referred to as "classical" shadowgrams). Fig. 3 shows a comparison of these images taken with the iXon+ EMCCD camera. All images were optimized in terms of illumination intensity and EM-gain. The reference image was taken without EM-gain through pure water. Then a suspension was continuously thickened until the target could not be imaged satisfyingly by classical shadowgraphy.

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This was the case either with or without EM-gain. The same suspension was then used with the Optical Kerr Shutter in place: the overall light intensity relayed to the EMCCD chip dropped significantly due to the suppression of the diffuse light but the transmitted photons can still be amplified over the noise floor to form a visible image of the object.

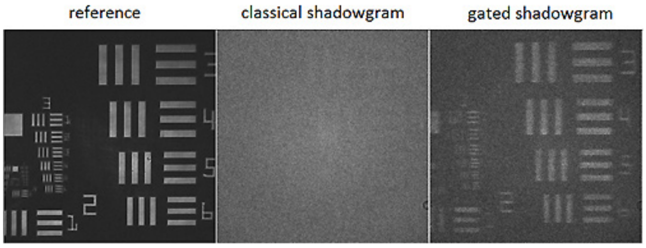

Figure 3: Images taken with the Andor iXon+ DU888 : reference shadowgram of the target through pure water (left), classical shadowgram of the target through a suspension of water and polystyrene particles with EM-gain 5x (middle), gated shadowgram through the same suspension with EM-gain of 300x (right)

References

[1] C. F. Powell, Y. Yue, R. Poola, J. Wang, Time-resolved measurements of supersonic fuel sprays using synchrotron X-rays, J. Synchrotron Rad., vol. 7, pp. 356-360, 2000

[2] M. Paciaroni, M. Linne, Single-shot, two-dimensional ballistic imaging through scattering media, Appl. Opt., vol. 43, pp. 5100–5109, 2004

[3] J. R. Gord, T. R. Meyer, S. Roy, Applications of Ultrafast Lasers for Optical Measurements in Combusting Flows, Annu. Rev. Anal. Chem., vol. 1, pp. 22.1–22.25, 2008

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