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Improvement of planar laser diagnostics by the application of a beam homogenizer

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Abstract. For planar laser diagnostics, a most uniform beam profile is highly desirable for two reasons: first, subsequent corrections for an inhomogeneous intensity distribution are time consuming and prevent on-line engineering assessment and second, temporal fluctuations cannot be corrected anyway. However, in general for combustion and flow diagnostics pulsed laser sources are used to achieve a high temporal resolution which typically possess a rather poor beam quality compared to continuously emitting laser sources. And, pulse to pulse fluctuations of the beam profile directly increase the noise in single-shot measurements. In this contribution we show the application of a micro-lens array based beam homogenizer whereby an almost homogeneous illumination of the region of in interest is achieved. This enables the on-line evaluation of the measured data without subsequent corrections. Thus a general advance of laser techniques towards engineering practice is achieved. Additionally, statistical fluctuations of the beam profile are strongly reduced by the homogenizer what directly improves the local standard deviation of the measurement. These benefits are demonstrated by means of planar laser-induced fluorescence (LIF) experiments.

1. Introduction

Planar laser based measurement techniques are well suited to investigate complex multidimensional phenomena like, e.g., the turbulent mixture formation in direct injection engines. Typically, a laser beam is formed into a light sheet and the signal is generated in the illuminated plane from scattering, fluorescence processes or emission of Planck's radiation. The signal is then collected by a suitable detection system, typically a CCD- or an intensified CCD-camera.

For quantitative investigations, it is highly desirable to achieve a most uniform illumination of the complete region of interest since subsequent spatially dependent intensity corrections are not always possible or tend to enhance the total measurement error because of their unknown variation with time.

However, for most of the mentioned techniques, pulsed high peak-power solid-state, excimer or dye laser sources have to be used in order to achieve the high temporal resolution necessary for the characterization of, e.g., turbulent flows processes. One of the major drawbacks of these laser systems is that they possess a rather poor beam quality compared to continuously emitting laser sources. Resulting from the actual design of the laser system, the lasers do not emit the flat top intensity profile desirable for quantitative measurements. Moreover, the pulse to pulse fluctuations of the spatial intensity distribution increases the noise in single-shot measurements. This is owing to, e.g., fluctuations in the laser medium, in the pump source or the stochastic nature of the pulse generation process itself.

Hence, two major problems reduce the benefit of the mentioned techniques for technical application namely temporally *stable* inhomogeneities of the spatial intensity distribution and temporally *fluctuating* inhomogeneities.

Besides correcting the overall shot-to-shot fluctuations of the pulse energy to a reference level by logging the output energy of each pulse, it is of common practice to normalize the instantaneous images of the scattering processes using an image recorded at defined reference conditions. However, the a-posteriori correction to reference conditions is not practicable in several fields. For instance for on-line sensor measurements or product engineering applications an in-situ interpretation of the measurement results is desirable. Moreover, the time-invariability of the reference conditions cannot be guaranteed for long-term investigations. Additionally, temporally stable inhomogeneities can be a problem, if the measurement principle is based on saturation effects, where the detectable intensities cannot be increased by further raising the laser output power [1-3]. Especially at the outer regions of the laser beam, the intensity of the laser fluence can reach values, where the condition for saturation of the signal is not fulfilled. For example in saturation LIF for minor species concentration mapping [4] or in laser-induced incandescence (LII) techniques, where the soot mass-fraction is measured via the emitted Planck-radiation after laser illumination (e.g. [5-7]), signal saturation may be aimed [8]. Ni et al. [7] explicitly note that laser beam profiles with uniform intensity distribution in the context of LII techniques would ease the monitoring of the local saturation efficiency and thus simplify the modeling of the heating and cooling mechanisms of the particles which drastically reduces measurement uncertainties.

In contrast to the temporally stable inhomogeneities which can be corrected to a certain extend, temporal fluctuations in the spatial intensity distribution cannot be accounted for and contribute directly to the measurement uncertainty, i.e., the standard deviation. In this context, a number of examples can be found in the literature where image corrections are applied but obviously do not fully remove the existing inhomogeneities (see, e.g., [9, 10]). Thus, the 2D interpretation of the measured signal is complicated as the measurement noise is a function of the position inside the measurement domain. One possible remedy is to detect the planar intensity distribution simultaneously to the actual measurement using an additional camera which is however connected with an increased experimental complexity.

In this work another approach to the described problem is shown which is experimentally simple to apply and comparatively inexpensive. A beam homogenizer is used to generate a mostly uniform intensity distribution in the measurement plane. Different experimental strategies for this task can be found in the literature, especially in the field of lithography and material processing (see, e.g., [11-13]). Depending on the application area, especially the homogenization by diffractive elements or microlens arrays has become accepted, mostly for homogeneously illuminating plane surfaces. Here, we have used two microlens arrays in conjunction with a Fourier lens to achieve a homogeneous illumination of the measurement plane for planar laser diagnostics. The fruitful influence of this device on the general quantification process of the measured planar signals is pointed out.

2. Experimental

Two experiments have been performed in order to demonstrate the advantages of spatially uniform beam profiles in the field of planar laser measurement techniques being generated by optical beam homogenizers. The performance of the homogenizer is first demonstrated by a laser induced fluorescence experiment with a tracer in a homogeneously purged flow chamber, including a statistical evaluation, followed by a LIF experiment in a turbulent premixed flame whereby the hydroxyl radical within the instantaneous flamefront is excited for fluorescence. First, the optical set-up, which is identical for both experiment will be shown, followed by the description of the individual experiment.

2.1. Optical set-up

Before the emitted laser beam travels through the plano-convex cylindrical focusing lens with f=500 mm (see figure 1), it passes through two parallel fused-silica microlens arrays (LA_1 and LA_2), consisting of 36 plano-convex cylindrical lenses each.

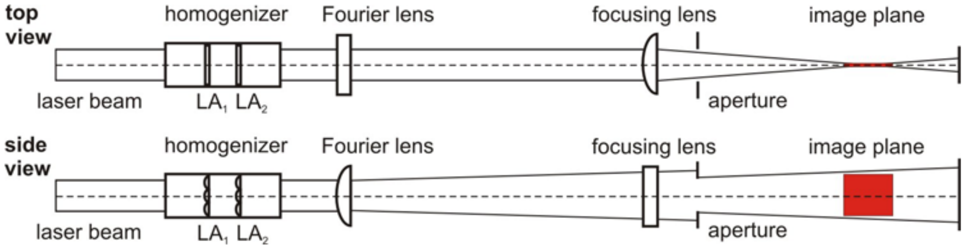

Figure 1. Optical set-up of the experiment.

The assembly of the two microlens arrays which is called beam homogenizer in the following results in a separation of the incident laser beam into several segments which are formed into slightly divergent sub-beams (figure 2). These sub-beams are then superposed on each other in the focal plane of a plano-convex cylindrical Fourier lens (f_{Fourier}=1000 mm), resulting in a homogeneously illuminated light-sheet. For the experiments without the homogenizer, the Fourier lens and the microlens arrays are removed. The laser-induced fluorescence signal is detected under 90° viewing angle by a fiber coupled, 2nd generation ICCD-camera (1024x1024 pixel) after passing through a filter combination of a Schott WG335 and a WG375 long-pass filter for the tracer-LIF experiment, and through the combination of a WG295 and an UG11 filter for the OH-LIF experiment, respectively. This was done in order to suppress elastically scattered light and flame luminescence. The signal from the image plane inside the flow-chamber is collected using a Soligor 90 mm f/2.5 objective, respectively by an UV-sensitive Nikon Nikkor 105 mm f/4.5 objective for the flame experiment.

2.2. Tracer LIF experiment

The beam of a narrowband KrF excimer laser (248 nm, 20 ns pulse width, maximum pulse energy of 250 mJ) is formed to a light-sheet inside the measurement area which is located inside a flow chamber. The latter is continuously purged with a homogeneous mixture of air and seeded acetone as fluorescence tracer (1.4 percent by volume). The chamber and the seeding procedure are described in Ref. [14]. For a statistical evaluation of the detectable signal, 512 single-shot measurements $I_i(x,y)$ were taken. The shot-to-shot fluctuations of the laser pulse energy were recorded by a whole-field energy meter and normalized to the maximum detected pulse energy. Each individual image was background-subtracted, corrected pixelwise for vignetting effects and then multiplied by a normalizing factor accounting for the time-dependent incident total laser pulse energy. Subsequent to this pre-treatment, a temporal average over the ensemble of taken images $I_i(x,y)$ was generated with the aim to

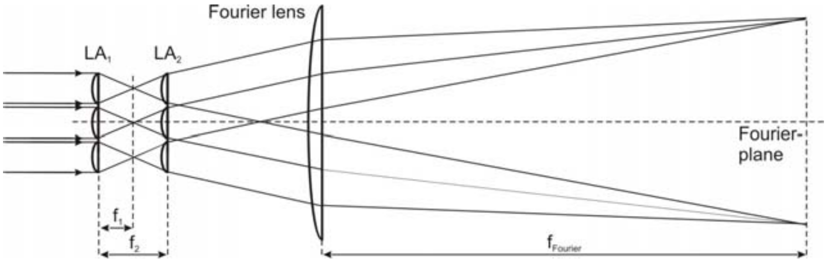

Figure 2. Schematic principle of beam homogenization.

compare the resulting temporally averaged intensity distributions with and without homogenization. In order to assess the property of the beam homogenizer to reduce the temporal fluctuations of the intensity profile significantly, the single-shot images are divided by the average image. From that normalized images, the root mean square (RMS) fluctuation is calculated by

$$\overline{I'_{RMS}(x,y)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{I_i(x,y)}{\overline{I(x,y)}}-1\right)^2} \tag{1}$$

2.3. OH-LIF in a turbulent premixed flame.

Here, the OH radical within a turbulent premixed methane-air V-Flame stabilized on a wire (see figure 3) with a fuel-air ratio ϕ=0.77 is excited by the second harmonic of a Nd:YAG-pumped dye laser (Pyrromethene 597 dye) near 283 nm. The burner has an outlet diameter of 48 mm, whereby the fuel-air mixture is generated in an upstream positioned static mixer. The stabilizing wire (1.6 mm diameter) is positioned 10 mm above the outlet. Air and methane are supplied by digital mass flow controllers.

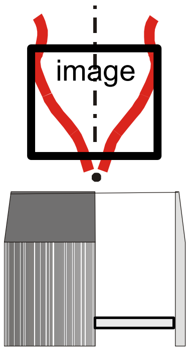

Figure 3: Burner set-up.

3. Results

3.1. Homogenization of the spatial intensity distribution

The application of the beam homogenizer for both the Tracer-LIF experiment as well for the OH-LIF flame front visualization results in an almost uniform intensity distribution. The resulting absolute intensity variation in the field is less than 5%. The residual inhomogeneities in the image in form of faint horizontal strips result from interference of the superposed sub-beams inside the measurement area and can be minimized by the adjustment of the homogenizer and the Fourier lens. Obviously real-time engineering investigations are facilitated by the application of the homogenizer since image corrections are now dispensable and the measurement can be evaluated directly.

Exemplary, we show a single-shot result, obtained from another planar tracer-LIF experiment for the concentration mapping of two different turbulent flows in the context of validation of sub-scale transport models in Large-eddy simulation [15] (see figure 4). Here the shear layer of both flows is illustrated, whereas the tracer is seeded to the flow on the left-hand side. The flow on the right side of the picture is unseeded. The false color image indicates high concentration on the left, the pure flow on the right is presented in black. It is emphasized, that the image in figure 4 has not been processed.

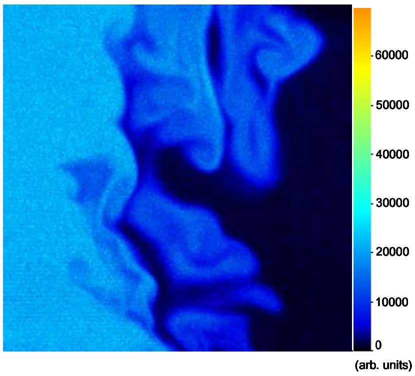

Figure 4. Exemplary non-processed image with applied homogenizer (shown is the single shot result of a tracer-LIF measurement of the mixing field of two different turbulent flows).

For dye-laser systems, the performance of the beam homogenizer is demonstrated in a turbulent V-flame. Two results from single-shot images without (figure 5, left) and with the utilization of the beam homogenizer (figure 5, right) are shown. The visualization of the flame front via the detection of the laser-induced signal intensity from the OH-radical as an intermediate product within the reaction zone is strongly influenced by the incident spatial intensity distribution of the dye-laser beam, which is clearly noticeable in the recorded signal intensity.

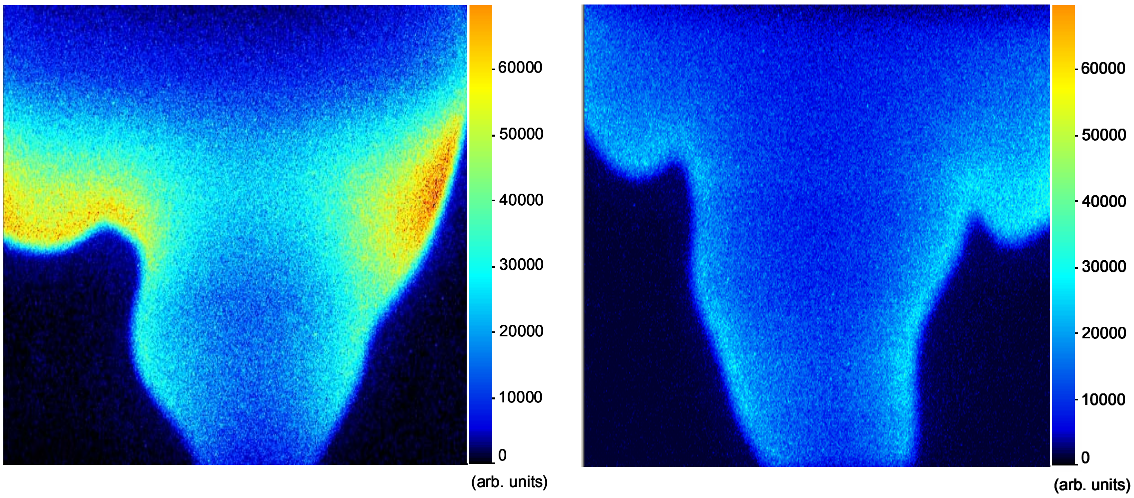

Figure 5: single-shot OH-LIF images ***without*** the application of the beam homogenizer (left) and ***with*** the homogenizer (right) resulting in the desired homogeneous "flat-top" beam profile

3.2. Comparison of the statistical fluctuations of the spatial intensity distribution

As deduced in Eq. (1), the improvements to planar laser measurement techniques with respect to the statistical fluctuations of the spatial intensity distribution of the illuminating laser beam, which can lead to high statistical errors, are displayed in figure 6 without and with the application of a beam homogenizer. The plot depicts a vertical profile of the statistical evaluation of an ensemble of exposures from the tracer LIF experiment performed in the homogeneously purged flow chamber.

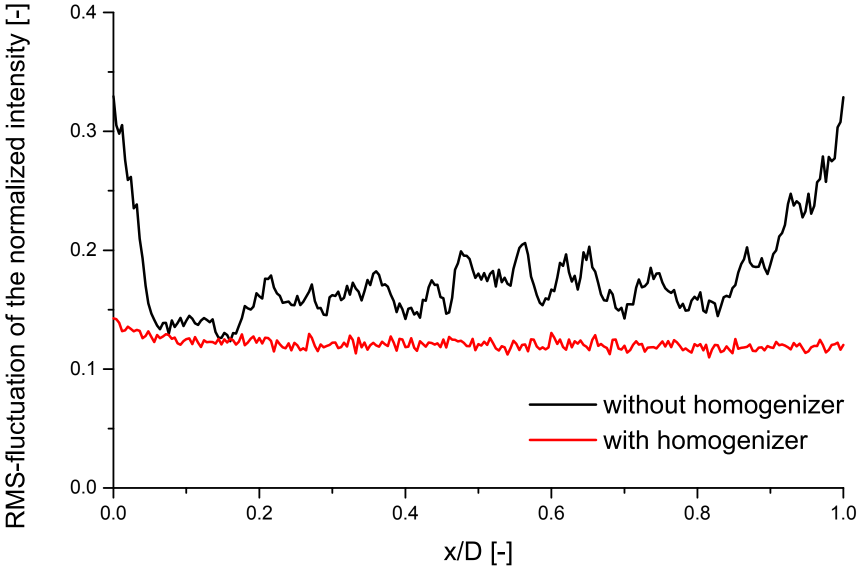

Figure 6 RMS noise of the normalized vertical intensity distribution with and without the homogenizer

A manifest spatial distribution of the fluctuations is obvious for the non-homogenized case (figure 6). The plot for the non-homogenized case characterizes clearly the stripes observed in many investigations, even where corrections for the inhomogeneous laser beam profile were performed (e.g. in [4, 9, 10]). Effectively, the application of the beam homogenizer smoothes drastically the spatial distribution of the averaged fluctuations (figure 6). All over the profile the statistical noise, especially evoked by temporal fluctuations of the incoming laser beam is almost uniform. Moreover it is worth to mention, that the absolute noise level has decreased conspicuously. The total amount of these fluctuations has reduced by 26 %.

The beam homogenization reduces the total measurement error close to the minimum practical achievable uncertainty, which is the overall-noise of the applied ICCD camera.

Thus, the reduced uncertainty achieved by the here presented beam homogenizing method reveals a direct improvement in the planar measurement of temperature, species concentration and fuel-air ratio measurement for the investigation of fluid dynamic phenomena.

At this point, it must be mentioned that for the application of this type of homogenizer, laser systems with a comparatively low spatial coherence must be used. Applying spatially highly coherent lasers leads to the interference of the superimposed sub-beams in the measurement area what can be seen for a highly coherent Nd:YAG laser beam in figure 7.

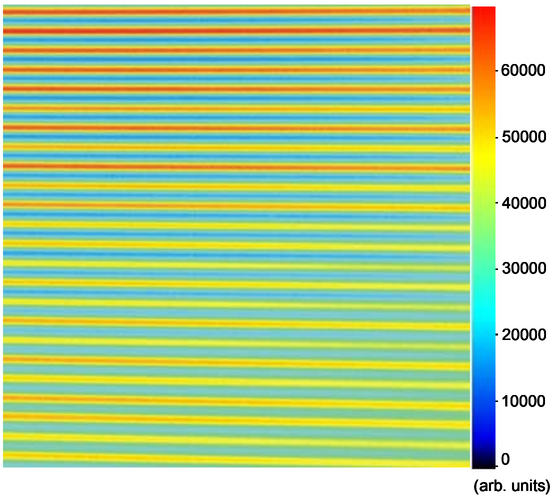

Figure 7: Interference stripes inside the measurement plane resulting from the application of a spatially highly coherent Nd:YAG laser

4. Conclusion

We have demonstrated the application of microlens array beam-homogenizers for planar laser techniques. It is shown, that the principle of beam-homogenizing for the illumination of plane surfaces can be established also for homogenizing high peak-power pulsed laser beams with the aim to gain a homogeneous spatial distribution on a line profile. By the application of the microlens arrays an almost uniform beam profile with a remaining non-uniformity of less than 5 % for the here presented experiments could be achieved. Thus, the direct evaluation of the measured data in terms of quantitative results without corrections for non-uniform profiles is enabled, what is of special interest for a further development towards engineering practice, where results from instantaneous, single-shot measurements have to be judged quickly.

Furthermore, the superposition of the sub-beams in the measurement plane significantly reduces the spatial fluctuations of the beam profile. The remaining fluctuations are uniformly distributed all over the measurement area. As a result, it could be shown, that the measurement uncertainty can be reduced to a level, which is close to the actual noise level of the used detector.

However, the reader has to be aware, that beam non-uniformities must not necessarily originate from the laser source like discussed in this work. They may be introduced also from the investigated object in case of a strongly inhomogeneous density field that introduces beam non-uniformities by beam steering from refractive index variations. This problem is discussed, e.g., in [16] and cannot be solved with the beam homogenizer. Another limitation of this type of homogenizer is that laser systems with low spatial coherence must be used, otherwise strong interference fringes are induced.

In future applications, the use of the homogenizer will prove even more valuable for nonlinear optical techniques (see, e.g., [17]). Here, the dependence of the signal on the spatial laser intensity distribution is much stronger than in the linear techniques discussed in this work.

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