High-speed structured planar laser illumination for contrast improvement of two-phase flow images

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High-speed structured planar laser illumination for contrast improvement of two-phase flow images

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A high-speed method to remove blurring effects caused by multiple scattering in planar laser images of two-phase flows is demonstrated. The technique is based on structured illumination and is for the first time to our knowledge applied on a dynamic medium. As structured illumination requires three successive images to be recorded and to freeze the flow motion in time, a high-speed laser and imaging system is employed. We show that by using a time delay of 55 μs between the images a single-shot representation of a dilute flow of water droplets can be achieved. By having an additional inner stream with known structure and composition, the efficiency of the method is quantitatively evaluated, showing an increase from 58% to 93% in image contrast. Such an improvement allows more accurate analysis and interpretation of scattering two-phase flow images.

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At present, the study of two-phase flows and other scattering media is mainly performed using laser imaging techniques. These modern optical diagnostics have numerous applications for biomedical as well as combustion engineering research. Depending on their source/detector arrangement, imaging can be performed using back, forward, or side scattering detection. One of the most popular side scattering detection methods, employed for flow visualization, is planar laser imaging. This approach offers both qualitative and quantitative spatially resolved measurements. Thanks to these advantages and depending on the physical quantities measured, various planar laser imaging diagnostics have been developed during the past three decades: particle image velocimetry [1], planar laser induced fluorescence [2], planar drop sizing [3], and droplet lasing [4], to mention a few. Although these techniques use different properties of light scattering and approaches, they are all based on the single scattering approximation, assuming that the detected photons have experienced only one scattering event prior to arrival at the detector. This assumption remains valid when the number density of particles is low and when the total photon path length within the probed medium is short. However, within optically thick media a large amount of photons are multiply scattered and the single scattering assumption is no longer valid. In this case, the multiple scattering blurs and attenuates the recorded images, introducing significant uncertainties in the detected optical signal [5]. This multiple scattering contribution is important in planar imaging owing to the use of both a relatively wide source of light and a large detection acceptance angle of the collection optics. Various procedures have been employed to correct and compensate for the light extinction along the laser path (using the iterative procedure of the Beer–Lambert law [6] or illumination from both sides of the probe volume [7]), but to our knowledge no technique has been proposed for the correction of the light being multiply scattered from the laser sheet to the detector when studying two-phase flow motions. In this Letter we investigate the possibility of suppressing this multiply scattered light by employing structured illumination in a planar laser configuration. A dilute flow of water droplets generated by a nebulizer was studied. For demonstrative purposes, the amount of multiply scattered light was increased in a second test by adding three nebulizers in front of the camera. Finally, the efficiency of the technique was quantitatively estimated by comparing the structured illumination approach with the conventional planar Mie imaging.

For a decade, structured illumination has been used in fluorescence microscopy for image improvements and was first demonstrated for backscattering detection by Neil *et al.* [8]. Recently, one alternative configuration shown by Breuninger *et al.* [9] consists in using structured illumination combined with planar laser imaging. This technique, single plane illumination microscopy-structured illumination (SPIM-SI), was applied on a static biological sample based on fluorophore excitation. In the setup presented by Breuninger *et al.* the total time delay for recording an image triple was 0.3 to 1 s. Contrary to the study of static objects, where time is not a restrictive parameter, the investigation of dynamic flows requires the motion to be frozen in time. The structured planar laser illumination setup presented in this Letter possesses a total time delay of 110 μs, short enough to capture the motions of the droplets. The field of view is $\sim$4 cm^2, and the Mie scattering signal is detected at 90° from the incident direction of the laser sheet.

Structured illumination is based on intensity modulation, in the spatial domain, of the excitation light, which can be created by projecting a grating onto the sample of interest. This enables blurring effects from multiple scattering to be suppressed in the image postprocessing. The main idea is that photons that have experienced several scattering events within the sample will lose the modulation information while singly scattered photons will not. Illuminating a grating leads to an image $I(x,y)$ [10] according to

$$I(x,y) = I_C + I_S \cdot \cos(2\pi v y + \phi_0). \quad (1)$$

This collected light $I(x,y)$ can be divided into two different images, denoted I_C and I_S. The first image I_C contains both singly and multiply scattered light and represents the conventional planar Mie image of the sample. The second image I_S contains mainly singly scattered photons and represents the structured laser illumination image. The cosine term describes the superimposed fringe pattern, which, to obtain the true I_S image, must be removed. This can be achieved by recording three images, I_1, I_2, and I_3, with the relative spatial phases (ϕ_0) 0, $2\pi/3$, and $4\pi/3$. This corresponds to a modulation shift of a third of a period between each image. However, the multiply scattered light, which is superimposed on the intensity modulation, is unaffected by this shift and is highly suppressed when implementing the following equation [8]:

$$I_S = \frac{\sqrt{2}}{3}[(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2]^{1/2}, \quad (2)$$

while the conventional image is obtained from

$$I_C = \frac{I_1 + I_2 + I_3}{3}. \quad (3)$$

In Fig. 1 an illustration of the experimental setup is presented together with an example of the three modulated images. The detection system employed in this Letter consisted of three 12-bit intensified CCDs, each with 960×1280 pixels. Each image, I_1, I_2, and I_3, was recorded from three successive laser pulses, which were created by two Nd:YAG lasers, one running in a single pulsed mode, while the second one was running in a double pulsed mode. All beams were recombined to spatially overlap. The grid pattern was shifted a third of a period between the three pulses by using a rotating plane-parallel quartz plate. The time delay between each laser pulse was 55 μs. This delay is governed by both the rotation speed of the quartz plate and the spatial frequency of the grating.

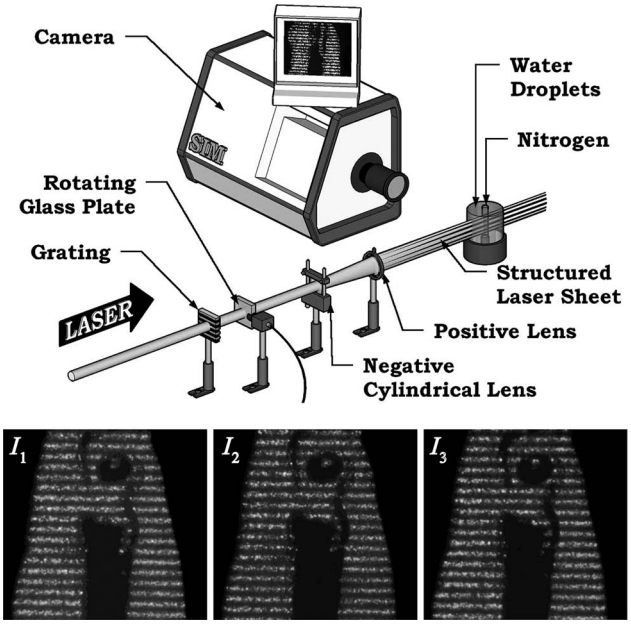

Fig. 1. Illustration of the imaging part of the experimental setup together with the three successive recorded images (I_1, I_2, and I_3).

To quantify the reduction of the multiple scattered light, an inner flow of nitrogen was introduced in the center of the nebulizer. In this region, where no scattering occurs, the intensity of the detected signal should, in principle, be zero. However, multiply scattered photons will falsely appear as originating from this region.

In Fig. 2 two different laser sheet measurements are presented. At the top, Figs. 2(a) and 2(b), mea-

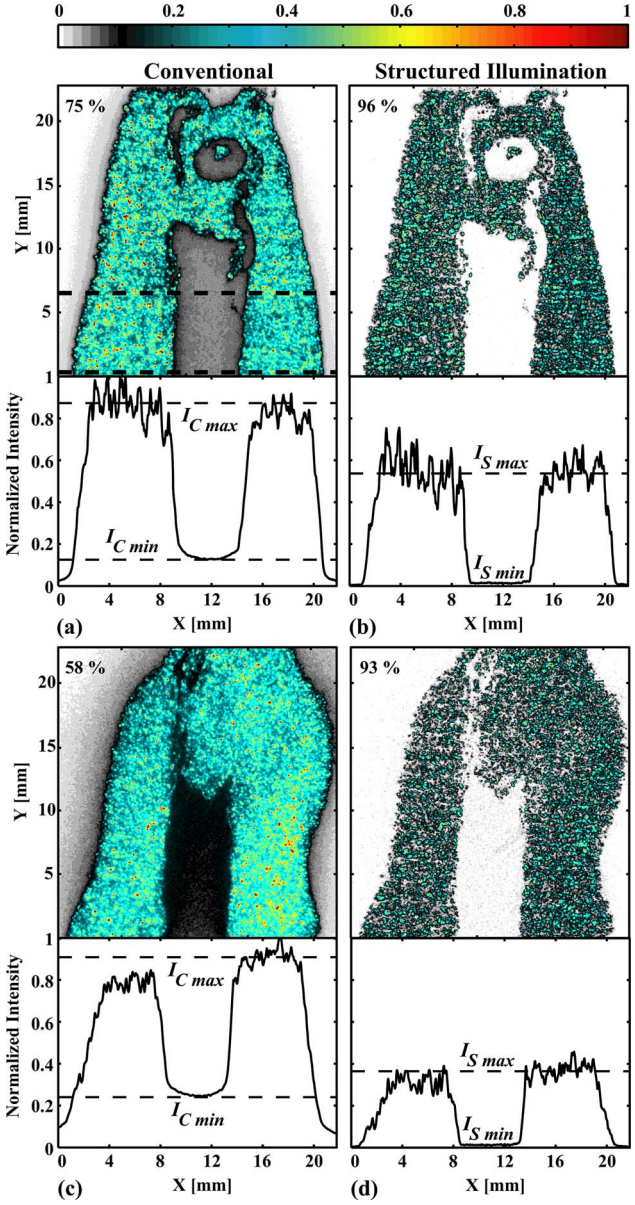

Fig. 2. (Color online) Comparison between I_C and I_S. In (a) and (b) a single nebulizer was used while in (c) and (d) three additional nebulizers were added in front of the camera. The estimated contrast value is indicated in the top left corner of each image. The cross section, integrated between 0 mm $< Y <$ 6 mm is shown below each picture, where the averaged maximum and minimum values are also indicated.

surements were performed with a single nebulizer, while Figs. 2(c) and 2(d) correspond to the case with the three added nebulizers in front of the camera. Figures 2(a) and 2(c) correspond to the I_C images, while the I_S images are shown in Figs. 2(b) and 2(d), respectively. To compare image contrast, a cross section, defined between the dashed lines shown in Fig. 2(a), is presented below each individual image. These intensity profiles are normalized with the cross section of each conventional image.

The effect of the multiply scattered light is clearly seen in the cross section of each I_C image. In the cross section for Fig. 2(a), an ~13% multiple scattering contribution is detected in the nitrogen region. When adding the three nebulizers in front of the camera, this effect becomes higher and reaches ~24% [see the cross section for Fig. 2(c)]. The multiply scattered photons give rise to a blurring effect in each of the three successive images I_1, I_2, and I_3. In contrast, the singly scattered photons that carry the structural information differ from image to image owing to the induced phase shift. The blurring features are removed by pairwise image subtraction [Eq. (2)]. This is demonstrated in the cross sections in Figs. 2(b) and 2(d), where $I_{S\,\mathrm{min}}$ tends to zero at $9<X<13$ mm.

For each image the contrast value has been calculated according to

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{4}$$

where $I_{\max}$ and $I_{\min}$ are indicated in Fig. 2. For the single nebulizer, the contrast increases from $C=75\%$ in I_C to $C=96\%$ for the I_S image, whereas, with the added nebulizers, C increases from 58% to 93%, respectively.

During the total time delay of 110 μs, a pixel to pixel displacement occurs for flow velocities larger than ~25 cm/s. By comparing three nonmodulated laser sheet images, it was deduced that this time separation, between the first and the last image, was adequate for this nebulizer. However, to investigate faster and denser two-phase flows, such as high-pressure injection sprays, this time delay must be decreased. This can be performed by increasing the rotation speed of the glass plate, as long as the momentum of the plate does not influence the measurement. Another approach is to use a thicker rotating glass plate. Also, the spatial frequency of the grating, which determines the required shift of the glass plate, could be increased. Finally, by using three gratings (instead of one) along each beam path, the rotating glass plate could be removed. In this case the minimum time separation will instead only be governed by the camera or the laser system.

In summary, we have demonstrated a high-speed structured planar laser illumination method suitable for two-phase flow visualization. The technique was evaluated on a dilute flow of water droplets based on Mie scattering measurements. It has been quantitatively demonstrated that a multiple scattering contribution of 24% in the central part of the image was reduced by a factor of 8. This suppression led to an image contrast improvement from 58% with the conventional technique to 93% with planar structured illumination. Such results indicate promising applications to denser scattering media, such as atomizing sprays.

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