Recent development of methods based on structured illumination for combustion studies

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Recent development of methods based on structured illumination for combustion studies

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Abstract: Structured illumination is an imaging method most commonly employed within the field of microscopy. However, recently the technique has spread into other scientific fields, such as for combustion research, where it has revealed new measurement opportunities. This paper describes how structured illumination can be employed for spray- and combustion research and highlights some of the recent progresses made towards temperature imaging, rapid data acquisition as well as detection of 'dark species'.
OCIS codes: (120.6780) Temperature; (110.2945) Illumination design; (110.2960) Image analysis; (110.7050) Turbid media.

1. Introduction

There are several challenges associated with laser diagnostics of combustion; events are transient and require rapid data acquisition methods, elevated temperatures reduce the molecular number density, leading to challenges for species detection, chemiluminescence and laser reflections cause background interferences that could be misinterpreted as a laser-induced signal, *etc*. This paper summarizes the recent work using structured illumination within this field, where the aim is to address and potentially overcome some of these experimental challenges.

2. Structured illumination

Structured illumination was originally developed for microscopic imaging, commonly divided into two different categories; *optical sectioning* [1] and *super-resolution imaging* [2]. Regardless of the end application, the method employs a certain illumination strategy, wherein the light field has a sinusoidal modulation pattern superimposed on its intensity profile, allowing the user to recognize the incident light and distinguish it from e.g. out-of-focus intensity contributions. The method usually involves the recording of three so-called *subimages*, between which the sinusoidal modulation pattern is shifted 1/3 of its period in order to illuminate all regions of the sample equally. Figure 1 shows an example the illumination scheme.

Figure 1. With the structured illumination method, the sample is irradiated with a light field having a sine wave pattern. Since not all regions of the sample is illuminated with a single beam, three acquisitions are required, between which the period of the sine wave is shifted 1/3.

3. Structured illumination for combustion studies

In 2008, Berrocal *et al*. demonstrated how to unify structured illumination with laser sheet imaging – a powerful combination, especially for spray visualization purposes [3]. An atomizing spray is composed out of an optically dense cloud of droplets. Light experiences difficulties both penetrating this cloud as well as exiting it, making it extremely challenging to measure e.g. the interior of such a spray. In most situations, the light finally reaching the detector has undergone several scattering events – a process that erases any information they might have carried concerning the spray structure. There is, however, a percentage of the light that retains such valuable information, namely the singly scattered photons. Berrocal *et al.* demonstrated that by means of structured illumination, these singly scattered photons could be extracted whilst discriminating against the multiply scattered ones, greatly improving visualization inside turbid, light-scattering media.

Since then the method, which was referred to as Structured Laser Illumination Planar Imaging (SLIPI), has been applied in several studies. By viewing the spray from two sides simultaneously, it was demonstrated that the method could be employed for quantitative imaging of the local extinction coefficient as well [4]. This quantity is important, as it carried information about the number density of droplets and their sizes.

3.1 Thermometry

SLIPI provides a solution to the multiple scattering problem but its merits have also proven important in other measurement situation, where the issue with multiple scattering is less severe. Laser Rayleigh scattering for 2D thermometry is such an example. This method takes advantage of the fact that the number density drops in high temperature regions in order to establish the temperature field [5]. Laser Rayleigh scattering is a relatively weak process, making it sensitive to background disturbances (usually caused by reflections and scattering upon surfaces). Unfortunately optical filters cannot be employed to reduce such interferences, as the method is based on detection of elastically scattered light. Because of these experimental challenges, the method is rarely used in harsh combustion environments. In 2012, Kristensson *et al.* demonstrated that by combining Rayleigh scattering and SLIPI, such unwanted background interferences – that does not carry the superimposed line-structure – can be minimized, leading to an improved measurement accuracy and temperature sensitivity [6]. Figure 2 shows a comparison between conventional- and SLIPI Rayleigh thermometry, recorded under relatively harsh measurement conditions.

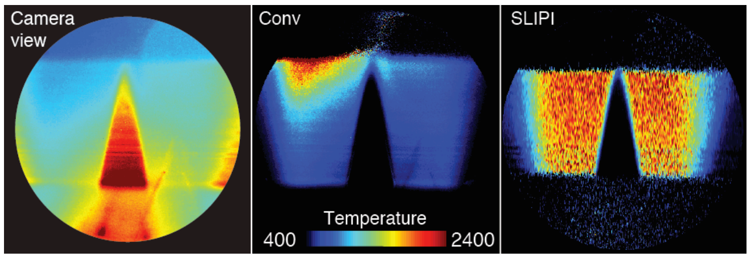

Figure 2. Comparison between conventional (middle) and SLIPI (rightmost) Rayleigh thermometry. The leftmost image shows the camera view.

3.2 Two-phase SLIPI

The need for three subimages in order to extract the 'final' SLIPI image leads to certain technical problems, especially when the method is used for combustion research where the objects of interest tend to undergo changes rapidly. Capturing transient behaviors thus becomes a challenge experimentally. In 2009, Kristensson *et al.* demonstrated an experimental setup capable of acquiring the three subimages within ~150 ns [7], but the approach relies on very advanced hardware – a cluster of high-power pulsed lasers combined with a multi-frame camera – which limits its applicability. More recently, a more practical methodology, based on only two subimages, has been presented by the same group [8]. When a SLIPI image is extracted from two subimages only (through the absolute of their difference), a gap in information is created, manifested as a residual line structure stretching across the final image. This is a well-known error and explains why the approach with only two subimages has been avoided in the past. Figure 3 shows an example of such a two-phase SLIPI image of a water spray, highlighting the unwanted residual lines. However, although the creation of such a residual line structure cannot be avoided, it can be controlled so that its presence has a negligible affect on the image quality. The method proposed by the authors exploits the fact that every imaging system has a limited resolving power, meaning that is can only observe spatial frequencies up to a certain limit. This limitation makes it possible to strategically 'place' the residual lines – which appear at twice the frequency of the superimposed sinus modulation – at a spatial frequency residing beyond the resolution limit of the imaging system. The benefits of structured illumination, such as improved depth-of-field, suppression of multiply scattered light and removal of background interferences can thus be exploited with only two subimages. Experimentally, this becomes very important as there are several instruments designed to acquire two laser images – but not three – in a rapid succession (double-pulsed lasers, interline-transfer CCDs, dual-frame sCMOS), presenting new opportunities to employ structured illumination for studies of dynamic events.

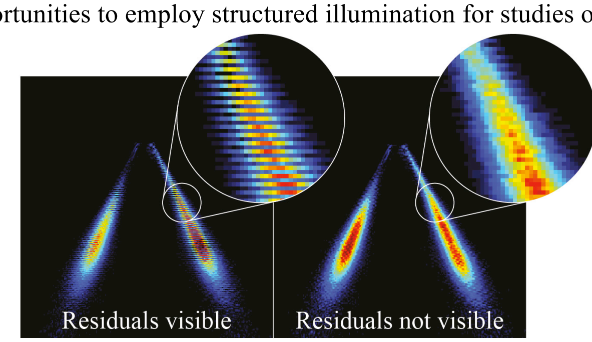

Figure 3. Two-phase SLIPI images of a water spray probed with two different modulation features. To the left, the modulation is chosen so that its corresponding residual lines become visible whereas to the right, the spray is probed with a sufficiently high spatial frequency, so that the imaging system fails to resolve the residual lines.

3.3 Laser-induced photofragmentation

Recently, structured illumination has also been used to measure so-called 'dark species', i.e. combustion species that cannot be directly probed via means of laser-induced fluorescence. Hydrogen peroxide (H_2O_2) is such a species. One approach capable of detection certain dark species is laser-induced photofragmentation followed by laser-induced fluorescence. In the process, an intense laser pulse – often called the pump beam – first dissociates the 'parent species'. In the case of hydrogen peroxide, the result is two OH molecules. A second 'probe' beam is then fired whose wavelength is tuned to stimulate the photofragments, thus revealing the H_2O_2 distribution indirectly. The concept works well under conditions where there are no photofragments (OH) naturally present in the sample, which unfortunately does not apply for most combustion studies. Instead, LIF signal from the naturally present OH molecules and the photofragments mix and one cannot easily deduce the H_2O_2 distribution. In addition, since the overall number density of naturally present OH often greatly exceeds that of H_2O_2, the signal-to-background is poor.

To improve the measurement reliability, structured illumination can be used. In the method, presented by Larsson *et al.* [9], the intensity profile of the pump beam is modulated, making the spatial distribution of the OH photofragments also modulated. The probe pulse still senses both kinds of OH molecules yet only those created via photofragmentation carries the modulation feature. By analyzing the acquired image using a spatial lock-in detection algorithm, the signal from the naturally present OH can be discriminated against. Figure 4 illustrates the data post-processing methodology. In Fig. 4a, the raw, unprocessed image is shown, containing signal from both naturally present OH as well as ones generated via photofragmentation. Removing the low spatial frequencies in the image reveals the modulated contribution, i.e. the photofragments (Fig. 4b). In reciprocal space – the Fourier domain – this modulation is clearly visible, appearing as two clusters of data symmetrically around the center. Each of these cluster components are actually 'copies' of the image, created when the modulated illumination multiplicatively interacted with the sample. By isolating one of these regions in the Fourier domain (Fig. 4c), it is possible to access this 'image copy', as shown in Fig. 4d. For more detailed information about the lock-in algorithm, see Ref [9].

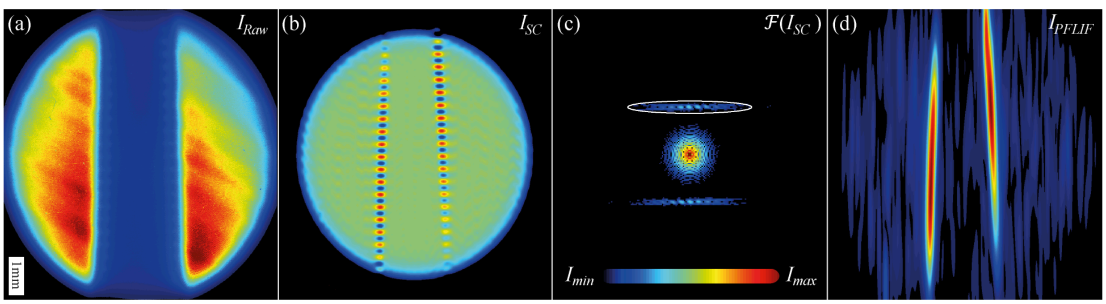

Figure 4. Spatial frequency lock-in detection method to extract the H_2O_2 distribution created via structured illumination photofragmentation. (a) The raw data, as seen by the camera. (b) The image in (a) without its low spatial frequencies. (c) The Fourier transform of (b), highlighting the modulated information, i.e. the H_2O_2. (d) The inverse Fourier transform of (c), revealing the distribution of H_2O_2 in (a).

4. Summary

Structured illumination is a laser-based imaging method based on coded illumination, taking advantage of the fact that a laser-induced signal not only carries information about the sample, but also about the illumination. Since background sources are unaware of this code structure, the method improves the signal-to-background. This feature helps in order to establish flame temperature, determine spray structures and measure 'dark species', for example.

5. References

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