Tomographic Particle Image Velocimetry using Pulsed, High Power LED Volume Illumination

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ABSTRACT

This paper investigates the use of high-power light emitting diode (LED) illumination in Particle Image Velocimetry (PIV) as an alternative to traditional laser-based illumination. The solid-state LED devices can provide averaged radiant power in excess of 10W and by operating the LEDs with short current pulses, considerably higher than in continuos operation, light pulses of sufficient energy suitable for imaging micron-sized particles can be generated. The feasibility of this LED-based illumination for tomographic PIV is demonstrated in this paper by measuring the turbulent velocity field in grid-generated homogeneous turbulence.

1. INTRODUCTION

High-power light emitting diode (LED) illumination provides an attractive alternative to traditional laser illumination for flow diagnostic and velocimetry for a number of reasons. Recent developments in solid-state illumination have lead to the ready availability of LEDs that provide radiant power in excess of 10W at a variety of wavelengths. By operating LEDs in pulsed mode at high currents, light pulses of sufficient energy and duration; suitable for tracer illuminating in flow velocimetry can be obtained. The use of LED illumination in flow diagnostic is not new [1, 2], however the generation of short duration double pulses and side-scatter illumination such as required for PIV is rather novel and has recently been pioneered by Willert et al., [3, 4] for water flow application.

Aside from the dramatically lower costs and considerable longer lifetimes, LEDs provide several attractive advantages in comparison to laser illumination such as extremely stable pulse-to-pulse intensity as well as prevention of speckle related artefacts due to their incoherent light emission. High-power LEDs can be pulsed at very high frequencies (>10kHz), while maintaining adequate pulse energy, which makes them very suitable for high-speed flow velocimetry. Owing to their relative large aperture, LEDs are particularly well suited for applications requiring volume illumination such a tomographic PIV (Tomo-PIV) or 3D-PTV. On this background, this paper investigates the use of pulsed, high-power LED volume illumination for tomographic PIV [5, 6].

2. HIGH POWER LED CARACTERISITCS

In this study, two different high-power LEDs of the type PT-120 available from Luminus Device Inc. [7] are investigated and listed in Table 1. The LEDs are specifically designed for projector systems and are available in a range of different wavelengths. Particularly green and red light LEDs are of interest here as modern imaging sensors exhibit peak quantum efficiency in the yellow to green range (530 < λ < 550nm), while the red LED provides the highest power output. Contrary to most commonly available LEDs these devices are essentially surface emitters with a nearly constant light distribution per unit area. Continuos operation of the LED at a forward drive current of $I_{f,CW}$ = 18A, as recommended by the manufacturer, produces an averaged luminous flux of θ_V = 2450lm, which corresponds to averaged radiometric flux of θ_R = 4.7W at a 50% duty cycle (green LED).

Emitter	$I_{f,cw}$ (A)	θ_V (lm)	λ_0 (nm)	$I_{f,max}$ (A)	θ_R (W)	A_{lum} (mm^2)
PT-120 (green)	18	3500	525	35	7.3	4.6×2.6
PT-120 (red)	18	1800	623	35	10.4	4.6×2.6

Table 1. Specification of selected high-power LEDs, [7]

The central aspect of high-power LED operation in this study is to pulse the LED with high currents over a short duration. This is achieved with a custom-built driver circuitry developed in [3] and used for planar-PIV measurements in [4]. The circuit is capable of delivering pulsed currents in excess of 200A with a pulse width in the range of 1µs < τ_p < 200µs at kHz repetition. Using pulsed LED operation at duty cycles <50% allows a drastic increase in drive current and hence light output beyond the recommend operating range of the LEDs. As an example Figure 1 plots the increase in luminosity for the green LED for increasing drive currents and various pulse

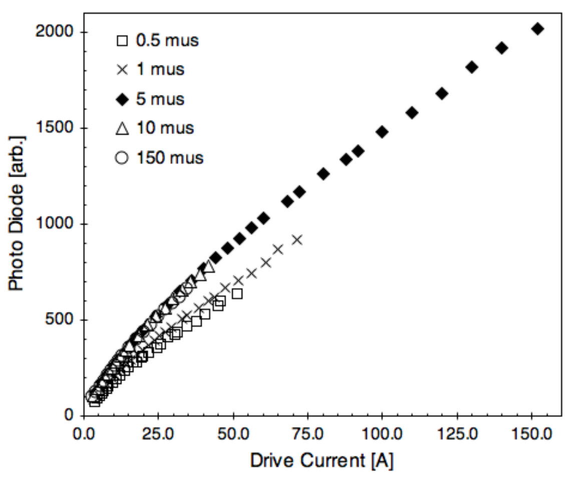

Figure 1. Increase in luminosity for current pulsed of duration between 0.5μs and 150μs at 10Hz (green LED).

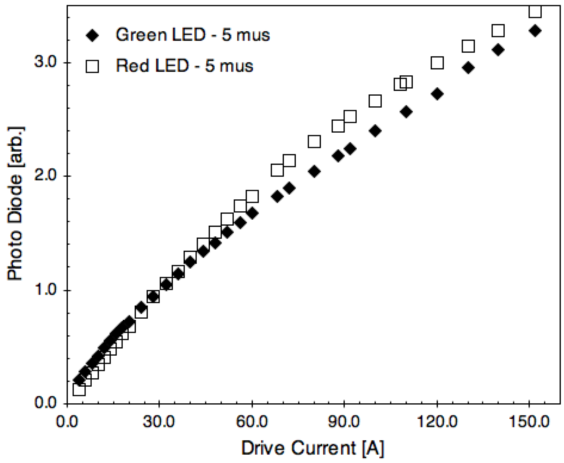

Figure 2. Increase in luminosity for the red and green LED for current pulsed of 5μs at 10Hz.

width as measured by a fast-response photo diode (Thorlabs, PDA10A). The data confirm the know increase of luminus flux θ_V with increasing drive current I_f. This leads to a proportional increase for low drive currents, while at higher currents, the proportionally decreases due to saturation effects of the LED. The red LED exhibits very similar behaviour (Figure 2) for low currents, but has a greater proportionality at higher currents. Both LEDs can easily be driven up to I_f = 150A, exceeding the recommended continuous drive current by one order of magnitude without suffering any noticeable damage. Two further features are worth remarking for the operation of the LEDs at high pulse currents. First, at longer pulse width (i.e. larger duty cycles) the maximum drive current reduces in order to avoid permanent damage to the LED. This damage manifests itself either through immediate failure of the bonding wires (very high currents) or long term thermal damage (medium current, long pulses) and is discussed in [4]. Secondly, for very short current pulses the response time of the driver circuit is to long and maximum forward current cannot be attained, which results in a reduced luminus flux at pulse width $\tau_p < 5\mu$s.

In Summary, when used in pulsed-mode, the present high-power LEDs can be operated at significantly higher drive currents to provide an increase in light emission compared to continuos operation. Measurements of the type shown in Figure 1 and 2 allow an approximate extrapolation of the luminous flux (or effective pulse energy) at such high currents. For example, the data sheet for the red PT-120 indicates a radiometric flux of θ_R = 10.4W when driven at a pulsed current of I_f = 30A and 25% duty cycle [7]. The effective pulse power for the duration of the current pulse is then 41.6W and as indicated by Figure 2, increasing the drive current to I_f = 150A increases the light output by a factor of 3.5. This produces a pulse power of nearly 145W and corresponds to approximately 145µJ for a 1µs pulse, which is sufficient to perform reliable PIV measurements in air [3].

3. TOMOGRAPHIC PIV WITH PULSED LED ILLUMINATION

Motivated by initial planer PIV measurement in [3] and [4] the present study focuses on using a single, high power pulsed LED for volume illumination of micron-sized particles suitable for tomographic PIV (Tomo-PIV) measurements. This concept is demonstrated in the following by measuring the turbulent 3C-3D velocity field in grid-generated homogeneous turbulent flow.

The experiments are conducted in a water channel with cross-section of 100 x 100mm^2 and a length of 1.2m. The turbulent flow is generated via a rectangular grid located 65 mesh units upstream of the test section. The mesh sizes is M = 8.25mm with a solidity of 0.426 yielding a mesh size based Reynolds number (Re_M=U·M/ν) of 900. The Tomo-PIV system consist of four digital CCD cameras (PixelFly, 1240x1024pixel^2), located under angles of 30º, ±45º and 90º on both sides of the water channel as shown in Figure 3. Water prisms are installed to reduce optical distortions at the solid/liquid interfaces and the Scheimpflug condition is set on all cameras to maintain focus throughout the measurement region. The cameras are fitted with 55mm Micro Nikkor lenses to produce an averaged optical magnification of approximately 0.15. The aperture is set to f# = 8 for the two 45º and 11 and 16 for the respective 30º and 90º camera to provide a depth of field greater than 10mm. Further details on the experimental setup can be found in [8].

To provide volume illumination the luminescent area of the LED is directly projected into the flow using a condenser lens for focusing. The flow is seeded with 21µm polyamid particles

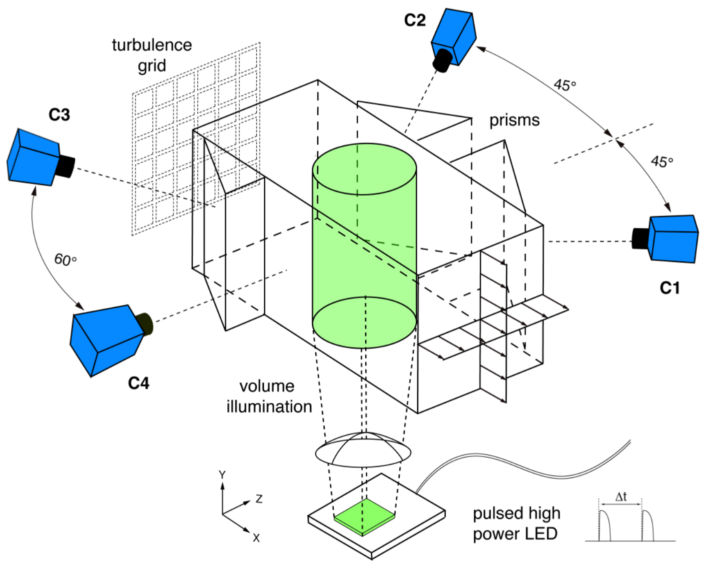

Figure 3. Schematic of the experimental setup showing the pulsed LED volume illumination with a condenser lens for focusing and the camera arrangement.

and images are acquired at a frame rate of 1Hz using the pulsed LED illumination. Current pulses of 24A and τ_p = 150µs duration with 1ms separation are used. Using information on the LED's optical power quoted in the data sheet along with the luminous flux increase plotted in Figure 1 and 2, the single pulse energy emitted by the LED is approximately 1.7mJ and 5mJ for the green and red LED respectively.

Prior to the Tomo-PIV processing the recorded particle images are pre-process involving background subtraction, dynamic histogram filtering and gaussian smoothing to the improve image contrast. The recorded intensity fields are reconstructed using a multiplied line of sight estimation followed by simultaneous algebraic reconstruction procedure (MLOS-SMART). Details of the tomographic reconstruction are given in [6] and [8] and are omitted here. From the reconstructed intensity fields the spatial variation of the emitted light intensity can be estimated and is plotted in Figure 4. The illuminated volume is approximately circular with an effective diameter of 8-9mm at 50% of the maximum intensity, which is roughly is 2-3 times the LED's luminescent surface area. The velocity fields are calculated with an in-house multi-pass FFT-based cross-correlation algorithm [9]. Interrogation volumes of 32^3 voxels with 75% overlap are used to provide fields of 57 x 117 x 43 vectors at a spatial resolution of 0.8mm and a grid spacing of 0.2mm. Spurious vectors are detected with a median test and replaced via linear interpolation and do not account for more that 1% of the total number of velocity vectors

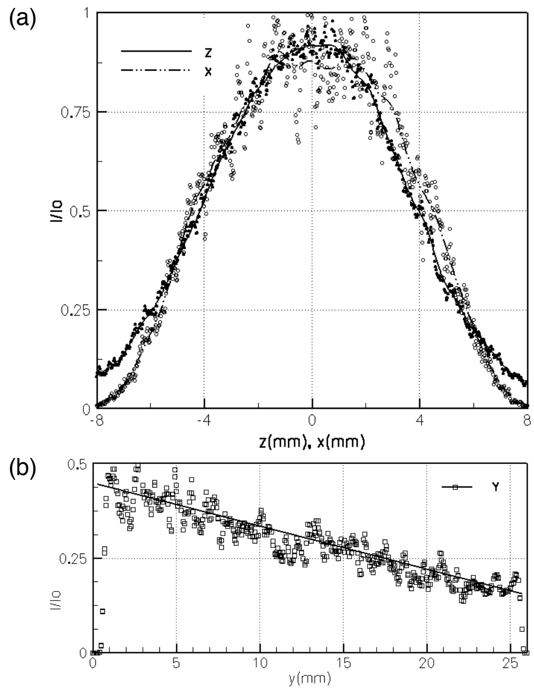

Figure 4. Averaged intensity along the (a) streamwise (x) and spanwise (z) direction and (b) vertical (z) direction. The extend of the illumination volume is estimated at 50% of the peak intensity

4. RESULTS

An example of the instantaneous three-dimensional vector field is shown in Figure 5a for a volume of 30η x65η x 24η. The mean convection velocity U is subtracted and the fluctuating velocity fields are filter with a gaussian kernel of size 2η x 2η x 2η. From the filtered volume data, the velocity gradient tensor is computed via a second order central difference scheme and Figure 5b shows contours of the normalised vorticity magnitude Ωη/U.

Figure 6 shows the PDFs of the streamwise velocity fluctuation for the two different LEDs compared with Tomo-PIV measurements using a Nd:YAG laser for illumination (cf. [8]). The fluctuations are distributed non-gaussian and closely track the results in [8], confirming the validity of the current approach. There is no significant difference between the red and green LED, yet the two LED distributions exhibit some larger variations due to the insufficient data quantity (N = 90 fields), which results in a poor statistical convergence. Concerning the turbulent statistics the LED results also agree well with previous measurements with a Taylor microscale based Reynolds number Re_λ = 11, turbulent intensity TI = 2.7%, dissipation rate ($\varepsilon = 2\nu S_{ij}S_{ij}$), $\varepsilon = 17.1 \cdot 10^{-6}$ m^2/s^3 and Kolmogorov scale η = 0.36mm .

The accuracy of the proposed LED illumination is assessed by considering the variation of the velocity gradient from the incompressible flow zero divergence condition. Fig. 7 shows

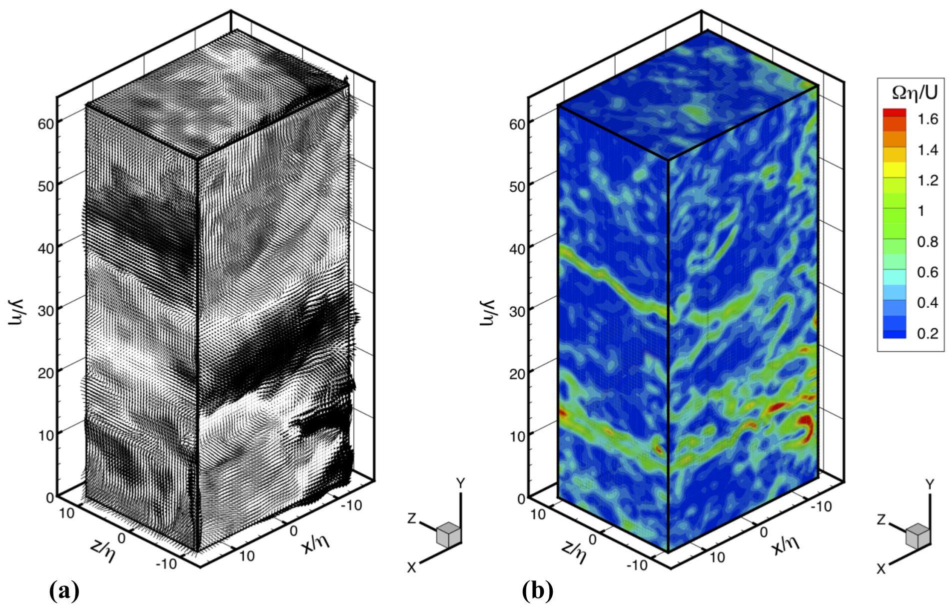

Figure 5. **(a)** Three-dimensional vector map of the flow field with the mean convection velocity subtracted; **(b)** Contours of vorticity magnitude normalised by the Kolmogorov length scale

the PDF of the divergence value ∇·u normalised by the norm of the velocity gradient tensor ||∇u|| for the red and green LEDs as well as for the measurements using the Nd:YAG laser illumination. In all cases, the divergence error is non-zero and the measurement uncertainty is directly related to the RMS (i.e. σ in Fig. 7) of the distribution. Overall, the divergence error is consistent with results in [10]. Interestingly, the LED data exhibiting a smaller divergence error, which is possibly related to the improved image quality and absence of pulse-to-pulse intensity variations (typical for Nd:YAG illumination), which leads to an improvement volume reconstruction. In fact the averaged cross-correlation coefficient for the LED measurements is about 0.69 compared to 0.56 for the measurements using laser illumination.

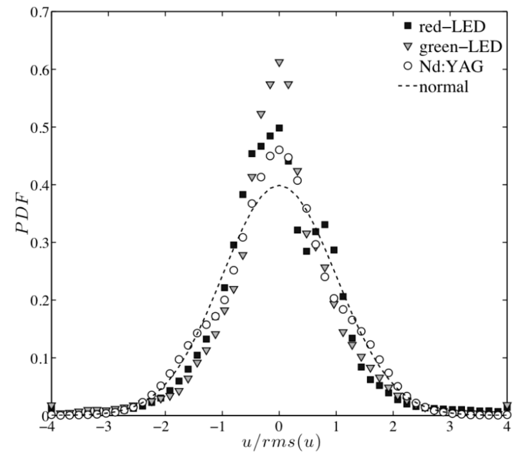

Figure 6. PDF of the streamwise velocity fluctuation for the red and green LED and comparison with Tomo-PIV measurements using Nd:YAG illumination.

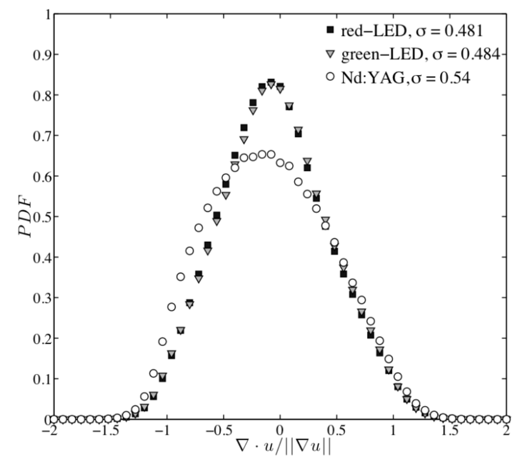

Figure 7. PDF of the normalised Divergence ∇·*u* / ||∇*u*||

5. DISCUSSION

The previously described experiment clearly demonstrates the feasibility of pulsed, high-power LEDs illumination for tomographic PIV. Being an uncollimated light source is one of the drawbacks of LEDs, which makes it difficult to establish quality light sheet illumination commonly obtained from laser-based illumination. This problem can be overcome by for example using fibre optics as demonstrated in [4] or by direct projection of the LEDs light-emitting surface into the test section. The large aperture of the LEDs makes this approach rather unique and provides quality volume illumination with some degree of collimation (i.e., by means a condenser lens). This makes LEDs an ideal illumination sources for velcoimetry techniques requiring volume illumination such as microscopic PIV, Tomo-PIV or 3D particle tracking.

The total amount of light emitted by the LED is proportional to the drive current (Fig. 1 and 2) and the pulse width. Operating the LED at high drive currents and large pulse width leads to overheating and irreversible damage to the LED (cf. [6]). The current measurements are performed at duty cycle of about 15% (150μs pulses with 1ms separation) producing approximately 1.7mJ and 5mJ for the green and red LED, respectively. Previous planar high-speed PIV measurements in water [3] used 20μs pulses at 50A drive currents, producing light pulses of approximately 400μJ. With further developments in LED technology occurring rapidly, even higher light output per unit surface area are very likely making further applications of pulsed LED illumination a viable alternative to traditional laser illumination.

9. CONCLUSIONS

The use of high-power pulsed LED volume illumination as a possible alternative to conventional laser-based illumination for Tomo-PIV measurements was investigated. Pulsed light at significant intensities was obtained from these solid-state devices by briefly overdriving them with high currents, which provides sufficient illumination for Tomo-PIV measurements in water.

PIV systems using LED illumination can be assembled at significantly reduced costs and multiple LEDs can be bundled together in compact, battery operated systems to increase the overall light emission and/or the size of the illumination volume. Due to their uncollimated light, LEDs are less dangerous, but not necessarily eye-safe and require considerable lower supply voltage than pulsed Nd:YAG lasers. In comparison with those lasers no pumping of the lasing medium is required meaning that LED light pulses can be fired with insignificant delay times (~10ns). Furthermore, the pulse repetition rate can be varied freely and does not depend upon a specific pulsing frequency. The broad spectral intensity distribution of the LED prevents the creation of speckle patterns and pulse-to-pulse intensity variation are practically not present. This results in an almost identical illumination of both exposures with good contrast, which is particularly desirable for Tomo-PIV applications.

Beyond the current application, the herein described LED illumination is also well suited for other techniques requiring volume and/or high-speed illumination such as shadowgraphy and high-speed schlieren (cf. [11]).

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