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Pulsed, High-Power LED Volume Illumination for Tomographic Particle Image Velocimetry

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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 them 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 grid-generated turbulence and a cylinder wake flow. Also, the use of LED illumination in time-resolved measurements is discussed.

Introduction

High-power light emitting diode (LED) illumination provides an attractive alternative to traditional laser illumination for flow diagnostic and velocimetry. Recent developments in solid-state illumination have lead to the ready availability of LEDs that provide radiant power in the excess of 10W at a variety of wavelengths. Furthermore, 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 (Chetelat et al., 2002, Estevadeordl and Goss, 2004), 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., (2009, 2010) for water flow application.

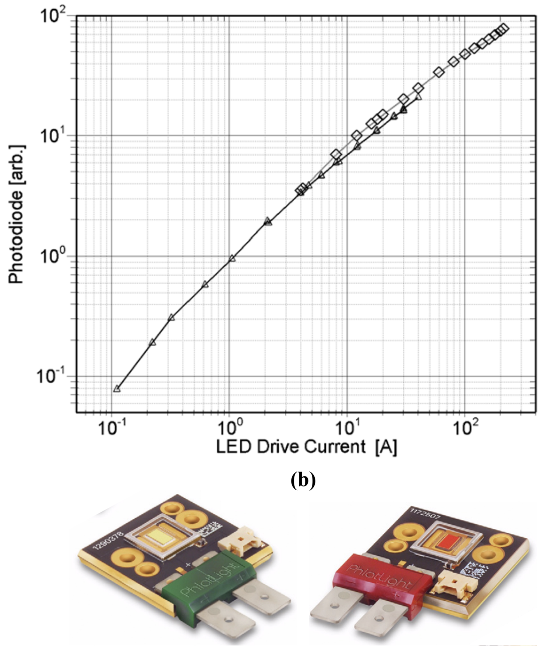
Aside from the dramatically lower costs and considerable longer lifetimes, LEDs provide several attractive advantages in comparison to laser illumination such as extremely stable pulse-to-pulse intensity as well as prevention of speckle related artefacts due to their incoherent light emission. High-power LEDs can be pulsed at very high frequencies (>10kHz), while maintaining adequate pulse energy, which also 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 (Elsinga, 2006; Atkinson and Soria, 2009).

LED characteristics in pulsed operation

The LED used in this study is a PT-120 available from Luminus Device Inc. and specifically designed for projector systems. Particularly green light LEDs are investigated here as modern imaging sensors exhibit peak quantum efficiency in the yellow to green range ($530 < \lambda < 550$nm). Contrary to most commonly available LEDs these devices are essentially surface emitters (4.6×2.6mm^2) with a nearly constant light distribution per unit area (see Fig. 1b). Continuos operation of the LED at the recommended drive current of $I_f = 18$A produces an averaged luminous flux of $\theta_V = 2450$lm, which corresponds to a radiometric flux of $\theta_R = 4.7$W.

The central aspect of this study is the pulsed operation of the LED with high currents over a short duration. This is achieved with a custom-built driver circuitry developed in Willert et al. (2010). The circuit is capable of delivering pulsed currents in excess of 200A with a pulse width in the range of $1\mu s < \tau_p < 200\mu s$ at kHz repetition. The increase in luminosity for the LED as a function of drive current is shown in Figure 1a. The LED can be driven up to $I_f = 220$A exceeding its recommended continuous drive current by one order of magnitude without suffering any noticeable damage. Figure 1a shows a proportional increase in luminous flux for increasing drive currents with an approximately 5.5 times increase in light emission at $I_f = 200$A (compared to continuos operation at $I_f = 18$A).

Figure 1a also allows an approximated extrapolation of the expected luminous flux and effective pulse energy at higher drive currents. According to the data sheet (Luminus, 2009), a radio-



(b)

(a)

Figure 1. (a) Increase in luminosity for current pulses of duration 1μs at 1kHz (Δ) and 10μs at 25Hz (◊). Figure reproduced from Willert et al. (2010); **(b)** PT-120 red and green high power LED.

metric flux of θ_R = 7.2W (θ_V = 3100lm) is obtained at a pulsed current of I_f = 30A at 240Hz and 50% duty cycle. Assuming a conservative proportionality of 35% light output increase with respect to an increasing drive current (Fig. 1) produces an effective pulse power of close to 60W at I_f = 200A. This corresponds to a pulse energy of approximately 60µJ for a 1µs pulse, which is sufficient to perform reliable PIV measurements in air (Willert et al., 2010). Further details on pulsed, high-power LED operation are given by Willert et al., (2010), including spectral analysis and damage threshold assessments.

Tomo-PIV using pulsed LED Illumination

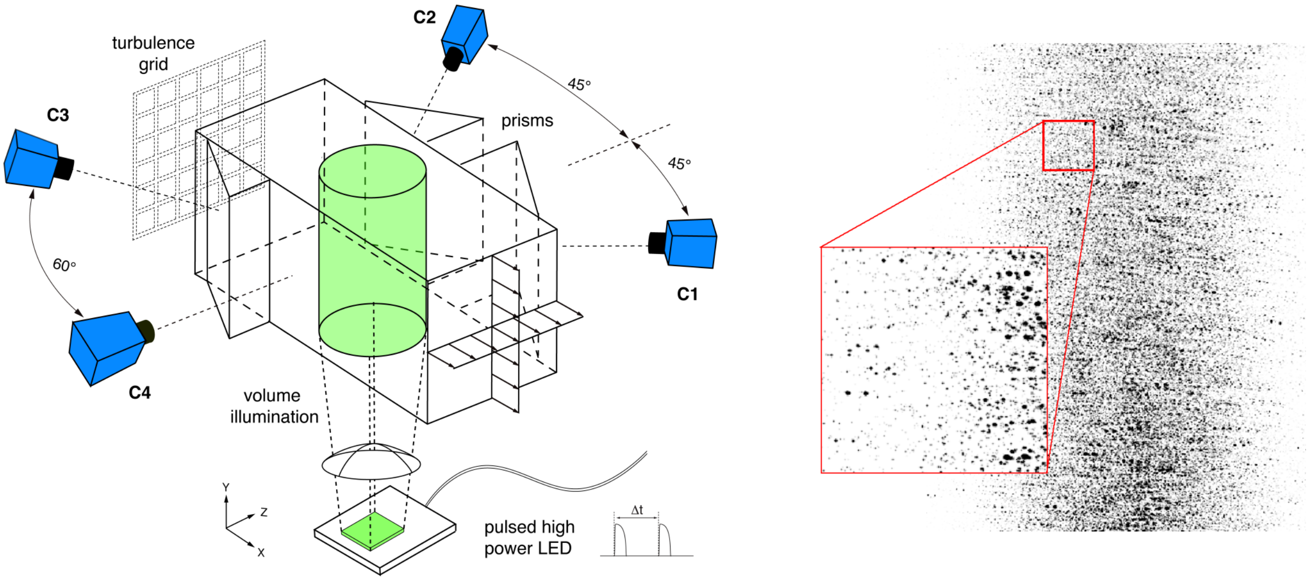
Motivated by initial planer PIV measurement (Willert et al., 2009, 2010) the present investigation focuses on using a single, high power pulsed LED for volume illumination of micron-sized particles suitable for Tomo-PIV measurements. The applicability of such volume illumination for Tomo-PIV is demonstrated in this paper by measuring grid-generated turbulence and a cylinder wake flow.

LED Tomo-PIV measurements of grid-generated Turbulence

The experiments are conducted in a water channel with cross-section of 100 x 100mm^2 and a length of 1.2m. Turbulence is generated via a rectangular grid located 60 mesh units upstream of the test section. The mesh sizes is M = 12mm with a solidity of 0.426 yielding a mesh size based Reynolds number ($Re_M = U \cdot M/\nu$) of 900. The Tomo-PIV system consist of four digital CCD cameras (PixelFly, 1240x1024pixel^2), located under angles of 30°, ±45° and 90° on both sides of the water channel as shown in Figure 2a. 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 yielding an averaged magnification of approximately 0.15. The aperture size is set to f# = 8 for the two 45° and 11 and 16 for the respective 30° and 90° camera to provide and estimated depth of field greater than 10mm. Further details on the experimental setup can be found in Buchmann et al. (2010). To provide volume illumination the luminescent area of the LED is directly projected into the flow using a condenser lens for focusing (Fig. 2a). The flow is seeded with 21µm polyamide particles and images are acquired at a frame rate of 1Hz using the pulsed LED illumination. Current pulses of 24A and τ_p = 150µs duration are used. Using information on the LED's optical power quoted in the data sheet along with the luminous flux increase plotted in Figure 1b, the single pulse energy emitted by the LED is approximately 1.7mJ.

Prior to the Tomo-PIV processing the recorded particle image are pre-process involving background subtraction, dynamic histogram filtering (Raffel et al., 1998) and Gaussian smoothing to improve image contrast. An example of the processed images is shown in Figure 2b. The recorded intensity fields are reconstructed using multiplied line of sight estimation followed by simultaneous algebraic reconstruction (MLOS-SMART). Details of the tomographic reconstruction are given in Atkinson and Soria (2009) and as well as Buchmann et al. (2010) 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 3. The illuminated volume is approximately circular with an effective diameter of 8-9mm at 50% of the maximum intensity, which roughly is 2-3 tiems the LED's luminescent surface area. The velocity fields are calculated with an in-house multi-pass FFT-based cross-correlation algorithm (Soria, 1996). Interrogation volumes of 64^3 voxels with 75% overlap are used to provide fields of 24 x 58 x 22 vectors at a spatial resolution of 1.6mm.

An example of the instantaneous, three-component, three-dimensional (3C-3D) velocity field is shown in Figure 4. The vector fields are colour coded by u, v and w and a convection velocity of U = 120mm/s is subtracted to highlight the fluctuating part of the velocity field. Furthermore, normlised PDFs of the velocity fluctuations are presented in Figure 5 and compared with earlier Stereo-PIV measurements in the same facility and flow conditions (Buchmann et al., 2010). The fluctuations are distributed nearly normally and closely track the stereo-PIV results confirming the accuracy of the current approach. Concerning the turbulent statistics the current results are also in good agreement with early reference measurements with a Taylor microscale Reynolds number of approximately 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 a Kolmogorov scale of η_k = 0.36mm.



(a) (b)

Figure 2. (a) Schematic of the experimental setup for the grid-generated turbulence experiment showing the pulsed LED volume illumination with a condenser lens for focusing and the camera arrangement; **(b)** PIV recording of water flow obtained with pulsed LED volume illumination. Both exposures are overlaid with the intensity scale inverted for better readability

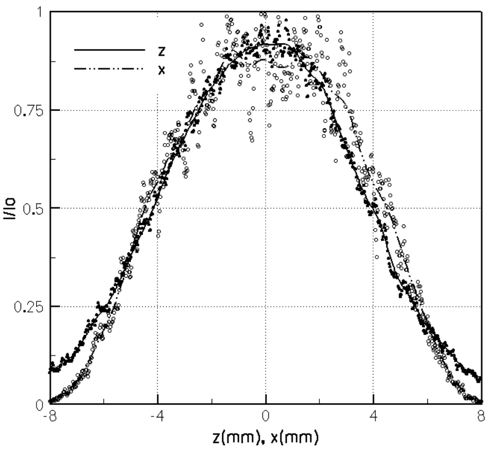


Figure 3. Averaged intensity profiles along the streamwise (x) and spanwise (z) flow direction. The extend of the illumination volume is estimated at 50% of the peak intensity

LED PIV in a cylinder wake flow

A second example includes the measurement of the 3C-3D velocity field behind an infinite cylinder (D = 6mm) mounted horizontally in the water channel shown in Figure 2a. The focus of this study is the development of a pulsed LED volume illumination at higher repetition rates (>100Hz) together with time resolved 3C-3D data acquisition to measure the spatial-temporal evolution of the cylinder wake at moderate Reynolds numbers (Re < 1000).

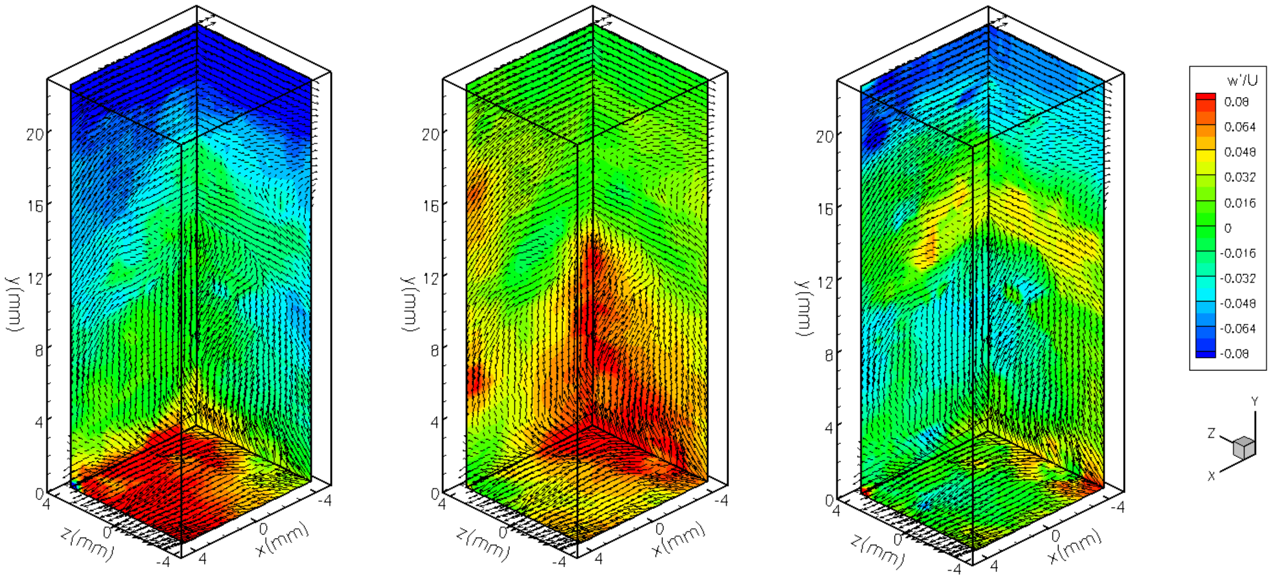
Initially, planar PIV measurements are conducted using a single camera (C4) and bundling of the emitted LED light into a light sheet by means of a fibre optics illumination system (Willert et al., 2009). The optical fibre bundle is round on the entry side (~3mm), while at the distal end the fibres are arranged along a straight line of 38mm and 0.5mm width. An approximately 1-2mm thick light sheet is then formed by projecting this line into the test section using a short focal length cylindrical lens (f = 25mm) for further focusing. Similarly to the previous study, the LED is driven with current pulses of approximately 24A and τ_p = 150µs duration providing sufficient illumination over an area of approximately 50mm^2. The LED is pulsed at the currently maximum possible camera frame rate of 12Hz. Higher pulse repetition are possible and have been tested and will be implemented at a later stage using high speed camera equipment. Similarly, the Tomo-PIV measurements are currently in progress and results will be present as they become available.

A sequence of three instantaneous velocity fields in the cylinder wake is shown in Figure 5 for Re = 360. At this Reynolds number, the vortex-shedding regime behind the cylinder is characterised by spanwise vortex pairs (*Mode B*) with a short spatial wavelength ($\lambda/D \sim 1$). Here only the streamwise evolution is shown. The separated shear layer is visible in form of a vortex sheet emanating from the lower side of the cylinder. On the upper side, a counter clockwise roller forms as indicated by the rotation of the instantaneous velocity vectors. The previously shed primary roller on the lower side detaches from the vortex sheet and convects downstream while the top role is still attached and evolving. This process is repeating, establishing the well know *Karman vortex street*. Knowledge about the spanswise evolution can yet not be obtained from these planar measurements, but are hoped to be available in the future by applying a similar volume illumination and Tomo-PIV analysis as in the previous example.

Discussion

The two previously described experiments clearly demonstrate the viability of using pulsed, high-power LEDs as an illumination source for tomographic and planar PIV. The herein reported PIV measurements of grid-generated turbulence and preliminary cylinder wake study involve LED volume and sheet illumination in a side scattering arrangement. Being and 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 elevated by using fibre optics such as in the second example and extensively discussed in Willert et al. (2010). Nevertheless, the rather large aperture of the LEDs means that they are well suited for volume illumination where collimation is of lesser importance. This makes them an ideal illumination sources for velcoimetry techniques 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. 1a) and the pulse width. Operating the LED at high drive currents and large pulse width will lead to



u'/U **v'/U** **w'/U**

Figure 4. Example of the instantaneous 3C-3D velocity field colour coded by the fluctuating velocity components u', v' and w'

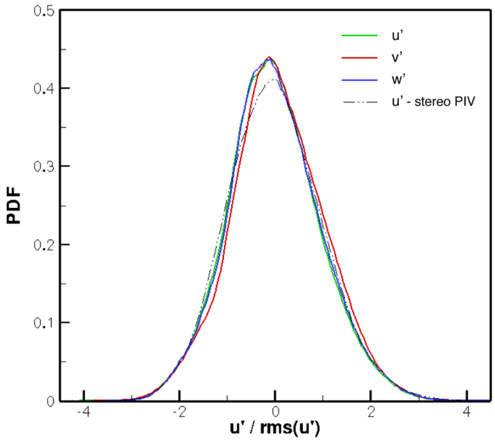


Figure 5. PDF of the fluctuating velocity components u', v' and w' and comparison with stereo-PIV measurements

overheating and irreversible damage to the LED. An envelope of "safe operation" for the current PT-120 LED has been previously established and is reported in Willert et al. 2010. The current measurements are acquired with duty cycle of about 15% (150µs pulses with 1ms separation). Future time-resolved measurements will have to be carried out at significantly smaller duty cycles (<10%) in order to avoid overheating and damage to the LED. Previous planar high-speed PIV measurements in water used 20µs pulses at 50A drive currents, producing light pulses of approximately 400µJ. This is a four times lower pulse energy compared to the current 1.7mJ obtained herein. However, further developments in LED technology will undoubtedly lead to even higher light output per unit surface area making further applications of pulsed LED illumination a viable alternative to traditional laser illumination.

Conclusion

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 and spatial variation are practically not present. This results in almost identical illumination of both exposures with good contrast (Fig. 2b), which is particularly desirable for Tomo-PIV applications.

Future work will be directed towards the development of LED arrays to increase the light emission as well as further developments associated with light collimation and volume and sheet illumination. Furthermore the present experimental will be extended to higher speed (>100Hz) 3C-3D measurements of the cylinder wake flow case. Beyond this, the herein described LED illumination is also well suited for other applications such as shadowgraphy and high-speed schlieren.

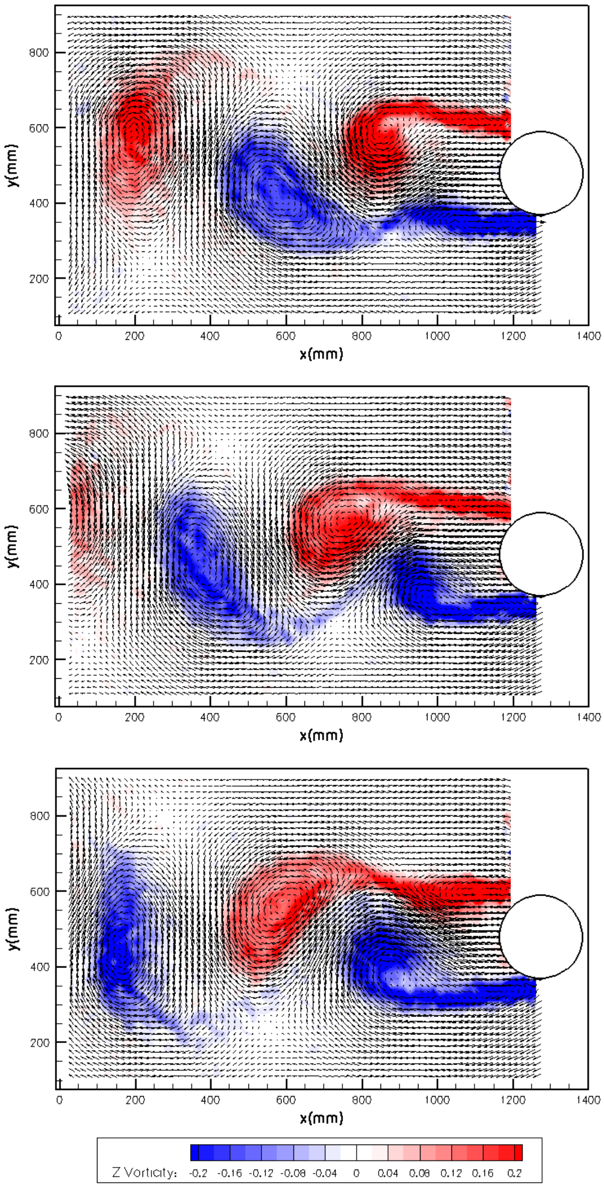


Figure 6. Example of three consecutive velocity fields behind the infinite cylinder as measured by planar PIV using LED sheet illumination. Data are recorded at a frame rate of 12Hz

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