# Pulse-length induced motion blur in PIV particle images: To be avoided at any cost?

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# Abstract

Low-cost illumination systems for Particle Image Velocimetry, such as pulsed laser diodes and LEDs are becoming increasingly popular. Due to the lower power output of these devices in comparison with flashlamp-pumped Nd:YAG lasers, they often have to be operated with longer pulse lengths to achieve a sufficient particle illumination. At some point, a longer pulse length will yield motion blurred particle images when the particles move at a certain speed. The root-mean-square error for different amounts of motion blur was determined for three sets of synthetic and experimental particle images. The analyses were performed in PIVlab, a free PIV software that is frequently used together with low-cost laser diodes or LED illumination. The results confirm that there is a negative impact of excessive motion blur on the displacement error. But when limiting the motion blur point spread function length to below 5 pixels, the additional error appears to be well acceptable for many applications.

# Introduction

Particle Image Velocimetry (PIV) traditionally uses a light sheet generated by a pulsed laser to illuminate particles that are suspended in a fluid. Cross-correlation of two images that are recorded in fast succession yields a space-resolved velocity field (e.g. Adrian 1984, Willert & Gharib 1991, Keane & Adrian 1992, Stamhuis & Videler 1995).

Pulsed lasers, such as double cavity, flashlamp-pumped Nd:YAG lasers deliver very bright laser flashes (e.g. 200 mJ per pulse) with very short durations (typically 10 ns). Although commercial systems are expensive and relatively bulky, these lasers are used predominantly in PIV studies (e.g. Ganapathisubramani & Clemens 2006). The cost for a commercial 200 mJ system with 15 Hz pulse repetition is in the range of 40k Euros, lower power systems with 1000 Hz easily exceed 100k Euros.

Another, more recent and increasingly popular approach to generate bright light sheets with low-cost light sources is to use LEDs (e.g. Chételat & Kim 2002, Willert et al. 2010, Bakker et al. 2021). These high-brightness LEDs have a large emitter area to generate sufficient light (e.g. 4 x 4 mm, Willert et al. 2010). Together with the large beam divergence of approximately 60 degrees, a collimation to generate a thin light sheet becomes difficult. This problem can be attenuated to some extent by using a fiber optic illumination system (line light) that has a more suitable emitter area of e.g.  $38 \times 0.5$  mm, and can subsequently be transformed to a relatively thin light sheet (2-3 mm) more easily. This setup can be used for PIV measurements in water with a small measurement area of e.g.  $25 \times 50$  mm and velocities up to 0.5 m/s (Willert et al. 2010). Several commercial solutions for LED PIV systems are available today. The hardware cost for a commercial system are an order of magnitude lower than a double cavity, flashlamp-pumped Nd:YAG laser, but clearly, a LED PIV system has a lower performance.



Figure 1: Array of four 5 W laser diodes, yielding a combined beam with 20 W.

Recently, the development of Gallium Nitride-based semiconductor lasers has made great progress: The output power has been increased, and the emission wavelength has been extended to the visible blue region. Therefore, blue multi-mode laser diodes with optical power outputs of up to 5 W have become increasingly available and affordable due to an increased demand in e.g. laser projectors (Scheibenzuber 2012). Although the emitted beam of these low-cost diodes has a high astigmatism, it is very suitable for generating a thin light sheet for Particle Image Velocimetry: A typical 5 W laser diode has a relatively large beam divergence of 10° (parallel to pn-junction) and 50° (perpendicular to pn-junction). But as the emitter area is very small (45 µm parallel to pn-junction, and 1 µm perpendicular to pn-junction), the beam can be collimated very well in the axis perpendicular to the pn-junction. This results in a very thin laser sheet. Furthermore, several diodes can be stacked together side by side without significantly impacting the thickness of the light sheet, resulting in very high-power outputs in a cost-effective design (see e.g. Figure 1). Even with a single 5 W laser diode, PIV measurements in water with a measurement area of 300 x 250 mm and up to 5 m/s are possible. Arrays of multiple laser diodes can also be used for PIV measurements in air. This is a significant step forward in comparison to LED PIV systems. Using specialized but straightforward driver electronics, laser diodes can be pulsed with frequencies up to 40 kHz and more. The cost for a laser diode-based PIV system can even be below the cost for a LED PIV system, due to a lower requirement for optics and lower cost for the current driver.

In comparison to double-pulsed Nd:YAG lasers that are predominantly used for PIV, pulsed laser diodes and LEDs are often operated at higher pulse durations (microseconds or milliseconds instead of nanoseconds) to achieve a sufficient illumination of the particles. When relatively long exposure times are used with particle images that have high particle velocities, then motion blur or particle streaks will appear in the recorded images. Motion blur in PIV data is believed to deteriorate the accuracy and robustness of velocity estimates: The reason is that the cross-correlation of motion-blurred particles yields asymmetric and broad correlation peaks, in which the location of the maximum is more difficult to detect with sub-pixel accuracy (e.g. Elsinga et al. 2005, Elsinga et al. 2005a, Ganapathisubramani & Clemens 2006, Elsinga & Orlicz 2015, Bakker et al. 2021, Oh et al. 2021, Qureshi et al. 2021). The extent of the negative effect of motion blur is sensitive to the cross-correlation technique and to the type of sub-pixel estimator that is used. Nobach & Honkanen (2005) have introduced a two-dimensional Gaussian regression sub-pixel estimator that addresses the problems of elliptically shaped, non-axially oriented particle images. It was shown that the error of the displacement estimate decreases substantially for elongated particle images (Nobach & Honkanen 2005), making it a suitable choice in combination with longer pulse durations.

# Methods

The aim of the present study is to give details about the relation between displacement uncertainty and the amount of motion blur, so users of diode lasers and LEDs have better information on how to decide for the best trade-off between sufficient illumination and motion blur. We therefore studied the effect of motion blur with synthetic particle images, printed, moving particle images, and 15 µm suspended particles moving at a known velocity, illuminated by a laser sheet. All analyses were performed in PIVlab, a very popular and free toolbox for MATLAB (Thielicke & Sonntag 2021). The software is often used in cost-sensitive experiments, hence low-cost illumination and the resulting particle image blur often is a topic. To describe the uncertainty of a measurement system, bias error and root-mean-square (rms) error are commonly used (see e.g. Thielicke 2014). Due to the selection of the PIV algorithm, the bias errors in the present study are considerably smaller than the rms errors, and are hence not explicitly shown.



Figure 2: Exemplary particle images. Top: Synthetic images. Middle: Printed particles, illuminated by a pulsed LED and filmed by a digital camera. Bottom:  $15 \mu m$ particles suspended in epoxy resin, illuminated by a light sheet from a laser diode and filmed by a digital camera. Left column: Minimum motion blur under test. Right column: Maximum motion blur under test.



Figure 3: Record player setup (shown with the 15  $\mu$ m suspended particles in epoxy resin): A record player rotates a petri dish with suspended particles at known velocity. A laser sheet illuminates the particles and the scattered light is captured by a digital camera.

## Synthetic images

Synthetic images were generated using PIVlab's image generator (see Figure 2, top). The particle diameter was set to 4 px  $\pm$  1 px, and the (uniform) displacement of the particles ranges from 0 to 10 pixels. The images were subsequently motion blurred with a point spread function (PSF) between 0 and 10 pixels (see details in Thielicke 2014). The direction of the motion blur is random and not related to the displacement. The per-pixel particle brightness was kept constant. The resulting images represent "optimal" synthetic particle images. To simulate "realistic" particle images, image noise (0.0005) and particle out-of-plane displacement (5%) was added (details on noise and out-of-plane displacement in Thielicke 2014).

#### Printed particle images

In a second experiment, particle images were printed on paper (see Figure 2 middle, Figure 3 and Figure 4), attached to a turntable, and filmed by a pco panda 26 DS digital camera with 25 megapixels. The individual particles had a diameter of approximately 6 pixels. The particle images were illuminated with a pulsed LED with different pulse lengths. The pulse separation was set to 2500  $\mu$ s, and the pulse length ranged from 250  $\mu$ s (= 10% of pulse separation) to 2500  $\mu$ s (= 100% of pulse separation). The displacement and the motion blur range from 0 px (center of the rotation) to 27 px (border of the rotation). The current through the LED was reduced for longer exposure times, so that the brightness seen by the camera was constant throughout the pulse lengths, avoiding overexposure with long pulse durations. Knowing the exact velocity of the turntable, bias and rms error could be determined.



Figure 4: A particle pattern was generated in PIVIab and printed on paper. The printed particle pattern was then attached to the turntable, illuminated by a pulsed LED, and filmed with a digital camera.



Figure 5: 15  $\mu$ m silver coated hollow glass spheres suspended in epoxy resin in a petri dish. The particles are illuminated by a 0.5 mm thick laser sheet generated from a pulsed 5 W laser diode. Reflections from the curved surface of the Petri dish are visible, leading to an inhomogeneous lighting – just as in real experiments.

## Suspended 15 µm particles

Experiments that mimic real PIV experiments were also performed: 15  $\mu$ m silver coated hollow glass spheres were suspended in water clear epoxy resin in a Petri dish (thickness of the slab = 10 mm, see Figure 2 bottom, Figure 3 and Figure 5). After curing of the resin, the Petri dish was placed on a turntable, illuminated by a 5 W pulsed laser diode (wavelength = 450 nm), and filmed by a pco panda 26 DS camera. The pulse separation was set to 2000  $\mu$ s with pulse lengths ranging from 20  $\mu$ s (10% of pulse separation) to 2000  $\mu$ s (100% of pulse separation). The displacement and the motion blur range from 0 px (center of the rotation) to 23 px (border of the rotation). Again, the current through the laser diode was reduced at higher pulse lengths to reduce the brightness with long pulse length and avoid overexposure.

All images from the experiments were analyzed using PIVlab's standard settings (window deformation, 4 passes) and the two-dimensional Gaussian regression sub-pixel estimator (Nobach & Honkanen 2005).

# **Results and Discussion**

The analysis of the synthetic particle images shows a small effect of increasing motion blur on the mean absolute rms error of the displacement estimates (see Figure 6). For "optimal" PIV images with no noise and no particle loss, the rms error is always below 0.01 pixels, and increases slightly with increasing blur. As expected, the "realistic" particle images have a significantly higher rms displacement error, and the error also increases slightly with motion blur. Other effects on rms error (here: noise and particle pair loss) seem to be much more important, shadowing the effect of motion blur. The study of Oh et al. (2021) shows that motion blur increases the rms displacement error in synthetic images quite dramatically. However, the study did not correct for the decreased brightness that is happening when blurring synthetic particle images. A decreased particle brightness will decrease the signal-to-noise ratio (SNR, Elsinga et al. 2005), yielding additional rms displacement error that is not per se caused by motion blur. In our study, we explicitly keep the brightness constant after blurring the synthetic particle images. The SNR will therefore not suffer from the decreased per-pixel brightness, but only from the broadened correlation peak. Furthermore, we are using a two-dimensional Gaussian sub-pixel estimator that is supposed to deal better with elongated correlation peaks. hence showing a relatively small effect of motion blur on the rms displacement error in synthetic images.





Figure 6: Motion blur that is applied to synthetic particle images slightly increases the rms displacement error in PIVlab.

Figure 7: Increasing motion blur yields higher rms displacement error for printed particles.

The results of the PIV analyses with printed particles show a more significant increase of rms displacement error with increasing motion blur (see Figure 7). The rms error is below 0.05 pixels for very small amounts of blur, but increases up to 0.3 pixels for large amounts of motion blur. It has to be kept in mind that 0.3 pixels rms displacement error with a peak displacement of 27 px corresponds to a relative rms error of approximately 1.1%.

The most realistic setup tested in this study are the 15  $\mu$ m particles, suspended in epoxy resin. Due to an imperfect alignment of the very thin laser sheet with the axis of rotation of the turn-table, out-of-plane flow and particle pair loss, as well as non-uniform lighting and reflections can be seen in the image data, just like in a standard PIV experiment. The rms displacement error increases almost linearly with motion blur up to 0.2 px (see Figure 8). At 40% pulse length, the particles have a significant motion blur (PSF) of approximately 9 pixels (see Figure 9). Here, the rms error is approximately 0.1 px, a magnitude that is widely accepted as typical uncertainty of PIV analyses (e.g. Nobach & Bodenschatz 2009). In this experiment, the maximum displacement was 23 pixels, hence the rms error amounts to approximately 0.5%.



Figure 8: Motion blur also increases the rms displacement error in an experiment with 15 µm particles, suspended in epoxy resin.



Figure 9: Particle image with 40% pulse length and approximately 9 px motion blur (PSF), yielding a mean rms displacement error of 0.1 px.



Figure 10: Particle image with 20% pulse length and approximately 5 px motion blur (PSF), yielding an rms displacement error of 0.075 px.

The choice of a suitable pulse length is generally a trade-off between sufficient illumination on one side and motion blur on the other side. Particle images that appear too dark will have a lower SNR, and an increased displacement error. To visualize this effect, we have generated a set of synthetic images which is the same as the synthetic "realistic" data set shown earlier (including the same noise and particle pair loss). But this time, we did not introduce any motion blur, but instead decreased the brightness of the particles from 100% to 25%. The results clearly visualize, that decreasing the particle brightness (while keeping the noise at the same level) does significantly increase the rms displacement error (see Figure 11) due to a lower SNR: At 100% brightness, the mean rms displacement error is about 0.05 px, which is very close to the rms error without motion blur in Figure 6. But as the particle brightness decreases, the SNR decreases, and the rms error raises up to 0.2 px. Decreasing particle brightness may hence have a larger negative effect on the rms error than particle motion blur.



Figure 11: The effect of particle brightness (in the presence of noise and particle pair loss) on the rms displacement error.

The experiments have also shown that there certainly is a negative effect of motion blur on the rms displacement error, supporting results from earlier studies (e.g. Elsinga et al. 2005, Elsinga et al. 2005, Ganapathisubramani & Clemens 2006, Elsinga & Orlicz 2015, Bakker et al. 2021, Oh et al. 2021, Qureshi et al. 2021). In the present study, particle images with extreme motion blur up to 27 px were tested. The results do also show, that motion blur, unless it is excessive, has a tolerable influence on the rms error of displacement estimates: The experiment with the suspended 15  $\mu$ m particles (see Figure 8) demonstrates, that the rms displacement error increases only moderately by 0.011 px for 20% pulse length, 0.039 px for 40% pulse length and 0.134 px for 100% pulse length.

In combination with the uncertainty that results from other sources in real PIV experiments, such as uneven particle illumination and calibration uncertainties, the additional error resulting from motion blur seems acceptable if the motion blur PSF is kept below approximately 5 pixels (see Figure 10 for an example). Very high amounts of motion blur (PSF  $\geq$  10 px, see e.g. Figure 2 bottom right) should be avoided to keep the rms displacement error low.

# Conclusion

When using low-cost pulsed illumination in PIV, a suitable balance between particle brightness and motion blur has to be found. Our recommendation is to limit the motion blur to less than 5 px, while trying to avoid over- and underexposure. This can be achieved by carefully adjusting the pulse length and the illumination power or detector sensitivity. In case of doubt, our results suggest that motion blur per se has less adverse effects than an insufficient particle illumination. Furthermore, a two-dimensional Gaussian sub-pixel estimator should be used for image data with motion-blurred particles. When striving for the lowest possible displacement uncertainty in PIV, parameters such as proper calibration, image distortion removal, low background signal and generally high signal to noise ratio are known to be very effective and can often be improved without increasing the expenses for equipment. Using high energy short pulses from sophisticated double-pulsed Nd:YAG lasers is certainly an adequate approach to decrease motion blur, and hence the uncertainty in PIV further. In cost-sensitive applications, however, the cost-benefit ratio of such a measure seems to be unfavorable as the negative impact of moderate motion blur (PSF  $\leq$  5 px, increase in rms displacement error = 0.011 px) appears to be acceptable for most studies.

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