Tomographic Particle Image Velocimetry Using Colored Shadow Imaging

Thesis by

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In Partial Fulfillment of the Requirements

For the Degree of

Master of Science

King Abdullah University of Science and Technology

Thuwal, Kingdom of Saudi Arabia

Insert Approval Date

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ABSTRACT

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by

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King Abdullah University of Science & Technology, 2015

Tomographic Particle image velocimetry (PIV) is a recent PIV method capable of reconstructing the full 3D velocity field of complex flows, within a 3-D volume. For nearly the last decade, it has become the most powerful tool for study of turbulent velocity fields and promises great advancements in the study of fluid mechanics. Among the early published studies, a good number of researches have suggested enhancements and optimizations of different aspects of this technique to improve the effectiveness. One major aspect, which is the core of the present work, is related to reducing the cost of the Tomographic PIV setup. In this thesis, we attempt to reduce this cost by using an experimental setup exploiting 4 commercial digital still cameras in combination with low-cost Light emitting diodes (LEDs). We use two different colors to distinguish the two light pulses. By using colored shadows with red and green LEDs, we can identify the particle locations within the measurement volume, at the two different times, thereby allowing calculation of the velocities. The present work tests this technique on the flows patterns of a jet ejected from a tube in a water tank. Results from the images processing are presented and challenges discussed.
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<tr>
<td>Bmp</td>
<td>Bitmap image file</td>
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<tr>
<td>CCD</td>
<td>Charge coupled device</td>
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<td>CMOS</td>
<td>Complementary Metal Oxide Sensors</td>
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<td>CW</td>
<td>Continuous wave</td>
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<td>DSLR</td>
<td>Digital Single-Lens Reflex</td>
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<td>fps</td>
<td>Frame per second</td>
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<td>JPEG</td>
<td>Joint Photographic Experts Group</td>
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<td>LASER</td>
<td>Light Amplification by Stimulated Emission of Radiation</td>
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<td>LED</td>
<td>Light emitting diodes</td>
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<td>MART</td>
<td>Multiplicative Algebraic Reconstruction Technique</td>
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<td>NEF</td>
<td>Nikon electronic format</td>
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<td>Particle image velocimetry</td>
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CHAPTER 1

Introduction

Tomographic Particle Image Velocimetry (Tomo-PIV) is one of several systems used to measure velocity fields in fluid mechanics. As all PIV techniques it tracks particle motions with time. However, it is the only technique which successfully can measure the full 3D velocity field in a volume and is increasingly being used for analysis of complex or turbulent flows. It has sufficient accuracy to allow calculations of all the velocity gradients and thereby to obtain the 3-D vorticity field, which is fundamental to the study of turbulence dynamics, through the study of coherent structures. For nearly the last decade since the seminal work of Elsinga et al. in 2006 [8], it has become a powerful tool and resulted in great advancements in conducting studies in the field of fluid mechanics [1]. Among these studies, a good number of researches have been published suggesting enhancements and optimizations in the different aspects of this technique, to improve its effectiveness and reduce the computational cost. One major aspect, which is the core of the present work, is related to the cost reduction of Tomographic PIV setup, using consumer cameras.

The remainder of this chapter provides introduction to the general PIV technique, discusses the standard setups of tomographic PIV, along with its main applications and limitations. It also highlights the commonly used illumination systems. The subsequent chapters will detail our modifications of the Tomo-PIV technique.
1.1 PIV Basic Principle:

PIV is a non-intrusive technique able to provide quantitative measurement of instantaneous velocity fields over a relatively large surface with measurements documented at a large number of points simultaneously. It first appeared in literature in the mid eighties for studying turbulence, and continued to be the most practical method and played major role in flow visualization [2].

The basic concept of PIV is to obtain the velocity from the short-term displacement of solid particles imbedded inside the flow-field (Figure 1.1). In other words, the

Fig 1.1: A schematic drawing showing Displacement of a tracer particle at two consecutive times
the velocity vector “\( \vec{U} \)” is calculated using the basic definition of a derivative, considering the tracer displacement “\( \vec{\Delta X} \)” between two successive observations. When the first observation is obtained at time “\( t \)” and the second one is at “\( t + \Delta t \)”, then:

\[
\vec{U} = s \frac{\Delta \vec{X}}{\Delta t}
\]  

(1.1)

where “s” represent the magnitude of the displacement, or length of the displacement vector. For high seeding densities, as used in PIV, the displacement of individual particles cannot be identified, but the most likely shifting of a collection of particles is obtained using cross-correlations.

1.2 Seeding particles:

For PIV to give accurate information about the underlying velocity field, the tracers must be small enough to follow the flow in presence of large local and randomly fluctuating accelerations. How well the particles follow the flow is characterized by the so-called Stokes number,

\[
St = \frac{\Delta \rho \ast \Delta u \ast d}{\mu_{liq}}
\]  

(1.2)

Where “\( \Delta \rho \)” is the difference in the density of the liquid and the particles, “\( \Delta u \)” is the velocity difference between the particle and surrounding liquid and “\( \mu_{liq} \)” is the
liquid dynamic viscosity and “d” is the particle diameter. Conceptually, the Stokes number compares the inertia difference between the particle and the surrounding fluid, vs the viscous force the fluid applies to reduces this difference in the two velocities. For the particles to faithfully follow the flow, the value of the Stokes number needs to be small. The most straightforward way of accomplishing this is to match the density of the particle as close as possible to that of the liquid [8].

Using small particles also helps in this respect. The particle also must be smaller than the finest velocity structures of the flow-field, to be subjected to approximately a constant velocity over its surface. However, the seeding particles cannot be too small as they need to be visible by the camera sensor. Small particles reflect less light than larger particles. Furthermore, the images of the particles on the sensor must be larger than the pixel size, to accurately capture them.

For standard PIV, a light sheet is formed by a pulsed light source to illuminate the particles. The duration of the illuminated light pulse must be short enough that the particles are almost still during each pulse. However, in our setup we use shadows, which have quite different optical properties than light scattering, but are also constrained by the same intensity requirements. The depth of field of the imaging also enters the optical design, as will be discussed in a later section.

1.3 Tomographic PIV standard layout:
A standard Tomographic PIV system consists of a pulsed laser with volume optics, which creates an illuminated volume slice in the flow, which is seeded with tracers.

Fig 1.2 Illustration of Tomographic PIV experimental setup and working principle, with 4 cameras and a laser volume-illumination [3].
The particle images are recorded with four digital cameras, which view the particle field from different directions. The cameras and illumination are synchronized using a computer to control the system, store the data and perform the required analysis.

In Tomographic PIV, the 3D velocity fields are measured using particle-based interrogation process, as illustrated in Figure 1.2. The process starts with having several camera-views of the tracer particles illuminated by the laser light sheet. These different viewing directions are captured simultaneously and the region of study corresponds to the overlap of all of these fields of view of the cameras. This is followed by reconstructing the three-dimensional particle field. In essence, this is done by triangulating the images from the different cameras and finding the location in 3-D where they overlap. In practice, this is done by an iterative reconstruction method called Multiplicative Algebraic Reconstruction Technique (MART).

Finally, when two particle-field volumes, taken at different times $t_1$ and $t_2$, have been reconstructed, we can use three-dimensional cross-correlation, on small sub-volumes within the larger volume, to obtain the local 3-D velocity vector, representing the particle motions. This provides velocity values over a regular 3-D grid spanning the entire measurement volume [3].

The illumination volume can be formed from different lighting sources as will be discussed in section 1.4. An important factor that affects the results is the exposure time, i.e. the duration of the illumination pulse. For best quality, one needs to ensure that the exposure time has to be short so that particles motion is “frozen”
without “streaks”. However, it should not be too short in order to guaranty a good illumination of particles for sufficient intensity needed for the camera sensor. Using Q-switched lasers this is usually not a serious constraint, as these pulses are typically around 5 ns long. However, for LEDs this needs to be optimized as will be discussed later.

For recording, the high-speed charge coupled device (CCD) or Complementary Metal Oxide Sensors (CMOS) video cameras are now commonly used since they have the capability to capture multiple frames at very high speed. The distance between the cameras and the orientation of their planes of view which is an important parameter to the imaging process and sensitivity to the out of plane motions. The magnification characterizes the pixel size on the sensors. The four cameras and the laser are connected through a synchronizer, which is controlled by a computer and dictates the timing of the camera sequence in conjunction with the firing of the laser [9].

1.4 Tomographic PIV Applications & Limitations:

Since its early development, Tomographic PIV has been widely used in many applications, such as the following areas [4]:

- Time resolved cylinder wake [11]
- Flow around a cylinder [14]
- Boundary layers [12]
- Round jet [4, 15, 16, 17]
• Shock wave [13]

Moreover, this technique proved to be a promising candidate in the ongoing research and development in different industries including the aeronautics and automotive and also in the medical and biological fields [3].

As with any other experimental systems, However, tomographic PIV has limitation factors. These factors were listed in the review by Scarano [1] and summarized below:

- High lighting power is required for illumination of a volume.
- The size of recorded images needs to be much larger than for regular planar or stereo PIV.
- The hardware used are of high cost and presents some safety concerns
- Large computational effort is required to analyze the recorded images as compared with the conventional planar PIV. This is particularly true of the 3-D cross-correlation.
- Complicated and sensitive 3-D calibration procedure.

1.5 Commonly used illumination sources:

The most common way of PIV illumination is by using the Light Amplification by Stimulated Emission of Radiation (LASER). This is because its ability to emit monochromatic light with high energy density, which can easily be formed into thin
light sheets. Light pulses can be obtained with pulsed lasers or with continuous wave (CW) lasers, when combined with a chopping system for producing light pulses and/or simply by shuttered recording of the video camera.

An optical system must be added to generate the illumination needed for specific purpose and each has its own importance. Lenses and mirrors are first used to generate from the laser beam a light sheet or light volume in the desired position within the test section. Second, two types of lenses are used: a cylindrical lens to expand the beam into a plane and a spherical lens to compress the plane into a thin sheet. Lastly, mirrors can be used to deflect the beam in the desired position, or scan it through the test volume [4]. Scanning beams have higher intensity when they hit the individual particles and can in that way improve the signal to noise ratio. The requirements of the optics for Tomo-PIV volume illumination are in a sense not as demanding as regular PIV, as the volume does not have to be as well defined, as the very thin sheets used in planar PIV. The Tomo-PIV processing extracts the 3-D location of the particles within the volume, whereas in regular PIV this location is determined by the laser sheet itself.

An alternative and effective method to obtain the needed illumination is by using high power Light-Emitting Diodes (LED). They can be used with a specialized PIV technique called particle shadow velocimetry (PSV) which has been validated through many PIV applications [5]. It works by focusing the LED light into a collimated beam which is directly toward the camera while seeding. The shadow of
the seeding particles will result in a bright background with negative appearance, or
dark region where the particles are present.

This illumination method features a significant cost reduction when
compared with the previous method. The output power can reach up to 1 mJ per
pulse when operated at high frequency. The handling and installation is simple with
least maintenance required. With recent developments of the blue LED, which
earned Isamu Akasaki, Hiroshi Amano and Shuji Nakamura the Nobel Prize in
Physics in 2014 [18], the entire visible light spectrum of wavelengths range from
460 nm in blue spectrum up to 645 nm in Red are accessible to in-expensive
illumination. Also it is workable with any type of cameras, from high-speed video
cameras to the normal low-speed digital consumer cameras.
CHAPTER 2

Objectives

The main objective of this work was to test a new technique to perform the Tomographic PIV in a more economical way, than the expensive specialized setups used in research laboratories today. Different setup was proposed that offers great cost reduction by exploiting the rapid technological advances, currently occurring in the lighting sources and the image recording devices. The consumer electronics technology is advancing by leaps and bounds, essentially following the Moore’s Law of chip development, by doubling in capability every 18 months [19]. Consumer cameras are in this way increasing the number of pixels of a sensor every year, with the most recent cameras having up to 50 Mpx on a single sensor. Video cameras with 4k sensors are similarly becoming commonplace, with frame-rates up to 60 fps. The newest 8k video has been announced recently. The idea is therefore to use consumer cameras for Tomo-PIV and ride this rapid advance to realize inexpensive experimental techniques for general use in research and industry. However, using single-frame cameras introduces complications regarding separating the two time-information of the locations of the particles. We propose to solve this by encoding the two images on the same frame, using the color information, green for one time and red for the other. Two inexpensive color LEDs are used to illuminate the measurement volume rather than the LASER which is usually used in standard setups. Likewise, normal low-speed digital consumer cameras replaced the very
Figure 2.1: Subsection of a Nikon photo demonstrating the basic idea of using two colors to embed time-information into a single image. Here a vortex ring is generated by rupturing a membrane, which spans the opening of a cylinder. This cylinder, which holds a suspension of particles, extends just out of the water surface, to give hydrostatic pressure to force the vortex ring from the bottom. The syringe needle is visible at the center, as two dark shadows, with the first shadow in the green color and the second in the red. Here the amount of particles is too high to perform Tomo-PIV, but they show clearly the overall motions. Note the fully dark shadows in the overlap regions, where both the green and red lights have been blocked, by a different set of particles.

expensive high-speed video cameras, or the specialized dual-frame cameras often used in PIV. Figure 2.1 shows a typical image from the Nikon camera, left after the two pulses. The red pulse comes first then the green, but the image seems to indicate the opposite. The explanation is given in the sketch in Figure 2.2.
Figure 2.2: Sketch showing how the shadows appear to reverse the order of the light illumination. In other words, the original location of the particle is marked by the green flash, which is the second flash. Similarly, the second location of the particle is red from the first flash, whereas the surrounding area are yellow, a combination of the two colors.

Figure 2.2 shows the technique in a nutshell. It shows the two shadows from one particle, which has shifted during the time between the background pulses. The first pulse is red and the particle is located at 1, marked in the figure. Then the particle moves to 2 and the green pulse is flashed. The final sketch show the intensities left on the camera sensor after the two pulses. Where both red and green have flashed on the same pixel the resulting color is yellow.
CHAPTER 3

Experimental Setup

The experimental setup for the novel Tomographic PIV technique, using the normal low-speed digital cameras and multi-color LEDs is illustrated in Figure 3.1 and consisted of the following components:

1) LED Illumination sources
2) Four DSLR Cameras
3) Specially designed water tank
4) Cylindrical chamber for seeding the system
5) Function and delay generators
6) In combination with the Davis Tomo-PIV software from LaVision.

3.1 LED Illumination Sources:

In this work we use colored-shadow imaging. The images of the particles formed as shadows, produced by illumination of a background diffuser screen. This screen is a thin sheet of drafting paper and is illuminated by ultra-bright LEDs. To produce a sufficiently bright background, we ended up using 4 separate LEDs for each color, i.e. a separate LED to backlight a diffuser screen facing each of the four cameras.
The same applies for the green and red colors, for a total use of 8 colored LED chips (Figure 3.2). The two colors are generated by consecutive electrical current pulses, so that each color indicates a specific illumination time. The light produced by each

![LED schematic diagram](image)

**Fig 3.1:** A schematic drawing for the LED system layout and octagonal water tank model.

LED unit is focused through an aspheric condenser lens (Figure 3.3) onto the diffuser film to make it evenly distributed. The emitted light has a wavelength of 623 nm and 525 nm in the red and green spectrums respectively. The drive condition for the red and green LEDs was set on 30 A giving output illumination flux of 1400 lm
Fig 3.2: Photos of the Red & Green LED Chips by Luminus [6].

for the red and 3100 lm for the green. The minimum pulse exposure time needed was 10 µsec and the time interval separating the two pulses ranged between 10-20 msec. However, for stronger particle contrast, we often needed to use longer exposure time of about 20 µs. Exposures longer than that would lead to significant smearing of the fastest particles.

Fig 3.3: A photo of the Aspheric condenser lens used with the LED system.
Using a function generator, the LED and camera systems were operated at 1 Hz through a delay generator that was used to synchronize both systems and control the timing. One reason for using such a slow frequency between subsequent pulse-sequences is to minimize vibrations of the cameras from the opening of the mirror, which must move out of the way before exposing the sensor. This issue can be avoided with mirror-less cameras, which are becoming more common (see for example new Sony 7R), or by disabling the mirror in the up position. Figure 3.4

Fig 3.4: Timing diagram for the LED and Cameras timing diagram for the Tomographic PIV setup.

shows a diagram for the timing of the LED and Camera systems. The timing sequence is the following:
i. The camera shutters are opened up and stay open for 1 sec.

ii. The green LEDs are turned on for about 100 µsec.

iii. After waiting for a time duration of about $\text{dt}=10 \text{ ms}$ the red LEDs are turned on for about 100 µsec.

The red and green LED chips were mounted next to each other on a common heat sinks for cooling purpose, as illustrated in Figure 3.5. The LED source including the LED evaluation driver cards and the heat sink are manufactured by Luminus, PhlatLight® [6]. LEDs can often be driven at higher currents for short durations than for continuous running, which would burn them up. In this way, one can get much larger illumination intensity for the pulses. This is quite crucial for Tomo-PIV, as the imaging of a volume demands small apertures on the camera lenses, to get sufficiently large depth of field. Smaller aperture, in turn, demands larger illumination strength, than would be required for planar measurements.
Fig 3.5: photo of the LED setup with lenses.
3.2 Cameras:

The Tomo-PIV images were recorded from a typically setup of 4 viewing directions using four DSLR cameras. The cameras were arranged symmetrically with viewing angle "θ" which is the angle between the outer cameras viewing direction and z-axis as illustrated in Figure 3.7. Since best results can be obtained at \( \theta = 30^\circ \), the cameras were placed accordingly [8]. The cameras used were Nikon D3X Model, single-lens reflex type with 24.5 Megapixels sensor size and capable of taking images at up to 5 frames per second (fps). In our PIV application, the cameras were set to record images at frame rate of 1 Hz and exposure of 1 second, which gives essentially single-shot imaging of the flow-field, unless the flow evolves very slowly.
The aperture was set on f-number of 11 (f-number is inversely proportional to the aperture). 50 mm Nikkor lenses were fitted on all cameras to have the same magnification. To minimize vibrations of the system the cameras were mounted on Manfrotto heavy-duty tripod heads, which were in turn mounted on X95 optical rails, as shown in **Figure 3.6**.

The triggering of the start of the camera exposure was initiated by the same delay generator that is used to control the LEDs pulses. Between the cameras and delay generator, the signal is converted and the cable is split into four cables terminated with 10-pin connections. **Schematic of the cameras connections is shown in figure 3.7**. For each experiment, two images are obtained by single camera exposure and two successive pulses of the different colors LEDs. The recorded images are saved in two formats: raw 14-bit format (NEF) and JPEG. The images are then uploaded to a specialized computer to be further processed and analyzed as explained in Chapter 4.
3.2.1 Camera calibration

To be able to triangulate the location of minute particles in the 3-D volume, it is crucial to have an accurate calibration, between every pixel on a sensor and the corresponding line it views through the illuminated volume. The accuracy of this calibration therefore has to be less than the particle size, or ideally less than the size of the pixel on the sensor. This requires an elaborate 3-D calibration procedure, which must be carried out in-situ, under exactly the same conditions as the experiment is conducted under. In other words, the test section must be full of
Fig 3.7: Schematic drawing & photo for the cameras connection.

water, both to have the same refractive index field as well as same shape of the outer wall, which can bend slightly due to the hydrostatic pressure from the water. The calibration of the four cameras was done simultaneously by using Lavision 3D calibration plate Type # 11 as calibration target (see photo in Figure 3.8 (a)). The plate size is 100 x 100 mm. The plate is made of black anodized aluminum, with numerous precision dots, each of diameter 2.2 mm with an in-between spacing of 10 mm. The plate surface has regular grooves to make the surface essentially represent two parallel planes of dots. The plate is traversed in a direction perpendicular to its surface, to calibrate through the volume.
A Pollux Motorized stepper-motor driven by a Micos controller shown in figure 3.8 (b) was controlled by personal computer to translate the plate in the z-direction over a total of 50 mm with 5 mm between each step. Eleven separate views of the calibration plate were in this way recorded so that it covers the whole measurement volume. The recorded images are saved in similar formats to the PIV images for further processing. The Davis program performs this calibration, to relate each pixel to the line cut through the measurement volume. It automatically finds the center of each of the white dots in each image. This is done separately for each of the cameras. In practice it is found that even this careful calibration procedure is not sufficient for the best results and a follow-on correction procedure is required for the best results, as will be described in the following section.

Fig 3.8: Photos of the calibration setup: (a) calibration plate by Lavision, (b) calibration stepper motor by Pollux.
3.2.2 Self calibration

This is done by using the actual particle images during an experimental run, rather than the calibration plate. In essence we search the particle images for especially bright particles, which are clear in all four cameras. If we know the identity of a particular particle, we can check whether the pixel lines from the different cameras intersect at a point in the reconstructed volume, as they should for a perfect calibration. The deviations from a perfect intersection can then be corrected. This will only work if the distortions are consistent between adjacent particle images, but not if these distortions are different for each particle in the field, which would indicate random noise. It may be surprising that this would work better than the highly controlled initial calibration using the translating grid, but in practice it has been noticed that things can change slightly between calibration to experimental runs. To list only one possibility for this change, it could be due to changes in temperature of the working fluid, when the experiment is running, which in turn will alter the refractive index, or expand the plexiglass walls, thereby shifting the lines which are extrapolated from each pixel on the cameras into the volume of the experiment.

3.3 Water tank:

Two water tanks were built for this work. The first one (Tank-A) was of a perfect octagonal shape (Figure 3.9) and the second one (Tank-B), more irregular one, as
shown in Figure 3.10. Both tanks were made from PVC and used as a medium for the PIV measurement. The experiment with Tank-A was associated with illumination system that consists of 2 LEDs per color and designed such that four cameras face two adjacent rectangular sides from front and two LED systems face two adjacent sides from backside.

The shape of Tank-B was designed to minimize optical distortions caused by the plexiglass walls. In the first design the viewing through the walls was at a slight angle, whereas in this new tank all the cameras look exactly perpendicular to the walls. This tank required 4 LEDs per color to get sufficient illumination intensity. This tank has a customized shape in a way that four camera views are identical, where they look through four adjacent rectangular sides and four LED systems face two adjacent rectangular sides.
Fig 3.9: Drawing and photo of Tank-A model used with 4 LEDs system.
Fig 3.10: Drawing and photo of Tank-B model used with 8 LEDs system.
3.4 Flow-field and Seeding system:

Seeding particles:

The particles selected for this application were glass microsphere (soda lime glass) with two different size ranges. For Tank-A model, 100-212 μm clear particles were used, while 90-100 μm silver coated particles were used for Tank-B model. The particles are supplied from Cospheric. The particles have a density of 1.36 g/cc.

Seeding mechanism:

The seeding is done using two Release mechanisms. For Tank-A model, a random mass of the seeded particles is dropped manually through 8 inch test sieve U.S.A std
made by Fisherbrand with Mesh size of 355 µm into the experiment medium (see Figure 3.11 (a)). While for Tank-B model, the seeding was done by ejecting premixed water with seeding particles into the experiment medium as shown in Figure 3.11 (b). In this part, a plastic bottle connected to an air tube was used. This bottle is covered from top with plastic tube that is having the pre-mixed solution of water and the seeds. The mix is sealed from air by a thin membrane. Then the seeding is obtained by applying sudden pressure generated by Air dispenser on the bottom of the membrane.

3.5 Signal & Air Generators:

The signals sent to the LEDs and cameras were generated using 3.1 MHz Synthesized function generator (Model DS 335) while the timing control and

![Fig 3.12: A photo of the function and delay generators.](image)
synchronizing was the part done by the Digital Delay generator (model DG645). Both the function and delay generators were manufactured by Stanford Research Systems (SRS). Photos of both generates are displayed in Figure 3.12.

The generation of air was through an air dispenser connected to an air source. The air dispenser is equipped with "SHOT" switch for checking shot volume and time. Using a regulator, the air pressure was set on 204 kPA to release the right amount of particles.
CHAPTER 4

Data Processing and results

Prior to starting the Tomo-PIV data reduction, several steps were necessary to transfer the raw RGB images from the Nikon cameras into a format that can be processed with the Davis 8.0 software from Lavision [7]. The Nikon NEF images, obtained during both the calibration and experimental runs, were first converted to tiff image files (tif), which are without compression. The uploading of these images from the camera memory to the LaVision software was done manually, at this stage and is therefore somewhat tedious. However, in future applications, this could be done automatically through a Matlab program. The image resolution remains as the original 5056 × 4032 pixels with 14-bit color depth. The subsequent steps explain the additional processing to split the colors and perform the 3-D reconstruction of each single color channel separately. The two reconstructions are subsequently combined to allow for the direct 3-D cross-correlation to find the 3-D velocity vectors.

RGB Image Color Splitting:

The process of color splitting represented a challenge to determine the positions of the red and green particles. As detailed below, analysis was performed on the particle images and revealed that clear separation of red and green shadows is hardly obtained especially where they overlap with high intensities.
Figure 4.1: Top panel: Original image using red/green shadows. This is a 2958x1968 pixel subarea of the full 24 Mpx image, where the particles in the vortex ring are visible. Bottom panel: Subsection of 500 x 300 pixels form the center of the above image, which has been brightened and its contrast enhanced. It highlights the very faint green particle images, as compared to the red images. This makes the separation of the two time-images difficult, as explained in the text.
Figure 4.1 shows a typical raw RGB image, while figure 4.2 shows one of the better enhanced images, which contains the two colors from the LED pulses. It is clear from the image that the green pulse is stronger on the left side and the red on the right side. The figure also shows a plot of the vertically averaged intensities for

![Image of RGB image and plot of vertically averaged intensities.]

**Fig 4.2:** Photo of RGB image and plot of the vertically average intensities of the colors.
Fig 4.3: Plots of the actual intensities with the particles (top image) and the average intensities of RGB image (bottom plot), where the spikes from the particles have been removed by averaging in the vertical direction.
Fig 4.4: Photos of particles before & after color separation of RGB image: (a) Enhanced RGB image, (b) Red channel, (c) Green channel, (d) Blue channel.

the three color components obtained by generating a MATLAB code. Here the
green flash is stronger on the left side of the image, while the red is stronger on the
right side. Such strong spatial variation in the background color makes it difficult to
write general programs to separate the two color shadows.

Similarly, other plots of average intensities were obtained and presented in
Figure 4.3, where the green color is stronger over the entire image.

Figure 4.4 shows the three different color channels RGB which constitute the
combined color image shown on the left panel. Even though the color image seems
quite easy to tell which is what, when looking at the Red channel we can see
shadows from both the red and green (see also Fig. 4.5 below). The green channels
is clearer. From this image it is clear that one must use some tricks to automatically
separate the two images, as will be explained below.
Figure 4.5: The details of an image subsection containing the shadows of one particle. When the particle is at location 1 the Red LED flash is illuminated and when it is at 2 the Green LED illuminates. The mid panel shows the three color channels along a horizontal cut though the center of the above image. The bottom curve shows the difference between the two LED colors, i.e. (Green – Red). The intensities are here in 16-bit format.
MATLAB program was also written to split the color image into red and green channels respectively. This produced two images, which represent the two positions of the particles separated by the time difference between the two LEDs. Example of image after color splitting is shown in figure 4.4. However, even though the two colors appear well separated in fig. 4.4(a), it can be noted here that an overlap exists in the Red component making it difficult to distinguish the respective particle’s position of this channel. This is even better shown in figure 4.4 where we plot the pixel intensities across these particle images. The bottom curves in fig. 4.5 show the intensities of the three color channels. The first pulse is red and the particle is located at 1, marked in the figure. Then the particle moves to 2 and the green pulse is flashed. The second green pulse fills in the original shadow from the red light. However, picture 50 shows that in practice this is not the idealized picture, as the green light has a big red component and therefore leaves a hole in the red where the particle is during the green flash. This very strong cross-talk between the two colors, makes the subsequent separation of the particle images from the two different times, difficult! This we have attempted in the following way.

The second green pulse is easier to separate, as it has clear lack of signal in the green channel. The first red pulse can be obtained by looking at the difference in intensities between the red and green colors. In Fig. 4.5(c) we calculate this difference (Green – Red) from Figure 4.5(b). This difference signal is positive and much sharper at the location of the first pulse, than at the second pulse. However, keep in mind that the specific particle image shown in this Figure is selected for clarity and many others are less clearly defined. Using this difference between red and green can work well over limited areas of the images, as is shown in figure 4.6.
Figure 4.6: The separation of the two particle images, by using the difference between the Red and the Green channels. This image is from a region with very sparse particle density. The dark particle images are much larger than the bright ones. However, keep in mind that this depends somewhat on the shifting of the zero intensity value, relative to the background.

However, this method shown in Figures 4.5 and 4.6 will not work all over the entire domain, due to the strongly varying background intensity of the different LED lights, which are not even, due to the large size of the LEDs, which do not fit at the center of focus of the lenses, shown in figures 3.5. The two LED chips facing each of the four cameras, use the same hemispheric lens to collimate the light to form a large spot on the diffuser, as was show in Fig.
3.5. The background variability of the two colors is shown along an average line in Figures 4.2 and 4.3. The intensities are functions of both x and y and over the entire image area it is larger than the particle signal. We therefore must first estimate and then subtract the local background intensities of the different color channels. To find this intensity, it is not enough to simply locally average the image, as the particles are ever-present and skew this estimate. We therefore find the average in a two-stage process. First, we use a moving average of 61x61 pixels, to calculate the average. Following this we do a smaller average over a 25x25 pixel area, but condition the average by the pixel intensity. In other words, if the value of the intensity is too far away from the first average, we discard this number, as it is most likely associated with a particle and not the background. In our preliminary Matlab program, this conditioned averaging takes a lot of computational power and we perform it only around every 5th pixel, filling the gaps with the same value. This is reasonable as the average background intensity changes slowly and not significantly over tens of pixels. This background subtraction can of course be optimized using matrix calculations and packaged software, but for our proof of concept, we are not very concerned about the extent of the required computation time, which is performed on our labtop computer.

If the particles are sparse it might be faster to sort the intensity values over all the pixels in the local pixel area and then simply select the median value.

This two-stage process provides the background intensity fields for each color channel, as are shown in Figure 4.8 for all 4 cameras. Here we have only shown the areas of the images which contain the vortex ring and where the three-dimensional reconstruction should take place.
Figure 4.7: The probability distribution of the intensity values of the pixels average over the entire area of interest, where the particles in the vortex ring are most visible. For this case this area is over a total of 6.847 Mega pixels. The green curve indicates the Green channel and the Red curve is the (Green – Red) channel. The local mean values of the intensities have been subtracted. The black curve corresponds to the red curve flipped about the zero value, to assess the symmetry of the distribution.

Ideally, the effective area of the flow should occupy the entire image, which should be possible with the appropriate optical setup (not reached at this stage in this experimental setup), which must take into account mainly three factors. First, the particle size (i.e. how many pixels span across each particle) should be of the order of 10 px, so the Bayer-filter on the camera sensor will not distort the particle location in the different colors. Secondly, the depth of focus of the lens should be sufficient to retain good focus over the whole relevant flow depth. This is primarily determined by the aperture of the lens, i.e. the smaller the aperture the larger the depth of focus. The trade-off is however the amount of light which reaches the camera sensor.
Figure 4.8: The average color fields for the four different cameras. The average eliminates the individual particle images, trying to approximate the background intensities. Where the particles are particularly dense, there can be areas of slightly darker patches.

The trade-off is usually an aperture of either 16 or 22. Thirdly, the number of particles visible through the depth of the imaging region should not give an image density which is more than 0.05 ppp (particle-per-pixel).

**Characterizing the pixel intensity fields for different colours**

One method we used to estimate the success of the colour separation was to look directly at the image intensity of the different colours. Figure 4.7 shows the resulting probability density functions (PDF) of the intensities of the green field and the (Green – Red) field. These pdfs have a very different shapes. While both are peaked around the background value, where the intensity is zero, the distribution of the green intensities is very skewed, with few positive
values. The skewness is -3.7 and the flatness an astounding 24. On the other hand, the (Green – Red) intensities appear slightly more symmetric, with almost as many positive and negative values, with a skewness of -3 and flatness of 28. The dark line is the flipped distribution around the zero value, which demonstrates differences between the two tails of the pdf, showing how far they are from symmetric. The skewness of the (Green – Red) is also towards negative values. This is of concern as we are trying to find the positive values. This opposite sign of the skewness is probably due to the large amount of cross-talk from the green flash. The tail of the actual intensity distribution is also much wider for the green color. The negative intensity-values in the tails of the distribution (away from the local background intensity) are exactly indicative of the presence of the particle, which is what we are trying to determine. This further highlights that it should be easier to extract the particle locations indicated by the green shadow, than the red shadow. The pdfs for the images from the other three cameras show similar characteristics. Figure 4.8 shows how uneven the background average red and green fields are for all four of the cameras.

**Images Pre-Processing:**

In the pre-processing step, image enhancements are applied using filters, background subtraction or mask overlays. Functions that were used included inverting to compute
Fig 4.9: Photo of a particle image (green component) after Unifying or subtracting background variation

the negative of the particles shadow images, smoothing to remove the noise, and masking to mask out the areas with low illumination. Examples of enhancements are shown in figure 4.9 & 4.10.

Fig 4.10: Photo showing Inverted green channel of particle image.
After merging the resulted data sets, the timing information was added and camera numbers were assigned for all frames. Having these steps done, the images were ready for 3D volume reconstruction. The results for each of these steps are presented below.

Figure 4.11-4.14 show the resulting separation of the two fields, Green and (Green-Red). In Figure 4.12 and we show the separated particles for the Green field, over the entire vortex ring, with Figure 4.12 focusing in on the left side of the ring, as viewed in each camera. The distribution of particles looks similar in all for views, indicating that the vortex ring is fairly axisymmetric. Figures 4.13 and 4.14 shows similar images for the Green-Red shadows. Clearly, this color-separation is not perfect and the images are much more pronounced in the Green channel. The particles in the Green-Red are also more “blotchy”, with outer noisy sections, which will affect the accuracy of the velocity fields. Figure 4.15 makes a direct comparison between the particle images from the two times, demonstrating that the Green channel has much sharper particle images.

Figure 4.16 shows direct correlation performed on the images, before they are used to reconstruct the 3-D particle locations. This is not expected to give reliable velocity vectors.
Figure 4.11: The particle images using the shadow in the green color-channel, from all four cameras. The average intensity has been subtracted first and the intensity magnitudes of the particle images has been adjusted to make the brightest images close to the maximum 8-bit intensity of about 250. Finally, the shadows have been inverted to make the background dark and the particles bright. The closeup marked by the red outline is show in the following figure. The width of each panel is about 2500 px. Close-up images are shown in the following figure.
Figure 4.12: Close-up particle images from the previous figure. The width of each panel is about 700 px.
Figure 4.13: The Green-Red fields for all 4 cameras, which correspond to the second time-flash. The following Figure shows more close-up images.
Figure 4.14: Close-up sections of the images in Figure 4.13.
Figure 4.15: Direct comparison of the particle images in the same area from the Green (left panel) and Green-Red (right panel) at the two different times.
Figure 4.16: Direct PIV calculated from the Tomo-images. Only the velocities at the outer edge of the vortex ring are close enough to two-dimensional to give good velocity results. The magnitudes of the velocity vector, indicated by the length of the arrows, look reasonable, with a strong decay away from the vortex core.

The vectors near the center of the vortex are obviously erroneous. This is easily understood due to the out-of-plane motion of particles due to the overall axisymmetric structure. This further highlights why tomo-PIV is needed for this type of study.
In section 4.2 we will show that using Red and Blue flashes works much better to separate the two time-flashes. However, this is demonstrated using only one of the Nikon cameras and the availability and intensity of the LEDs in the lab, did not allow us to pursue this color-combination in this theses and will remain for future work. We therefore attempt to use the Red/Green combination in this thesis, but knowing that future improvements are possible with the Red/Blue lighting.

**Volume self-calibration:**

As explained in section 3.2.2 it is necessary to correct the original calibration by performing the so-called self-calibration, to correct the calibration coefficients. From averaging these inaccuracies, 3D disparity maps are generated and the calibration function is corrected accordingly. In our experiments for a proof of concept we skipped this step. However, by showing below that we are able to get reasonable velocity fields without self-calibration, one can expect to get an improved result if self-calibration is included. Indeed being able to produce any reasonable velocity field without the self-calibration indicates that our initial calibration is of quite high quality.
Figure 4.17: The intensity distribution of the particles in the reconstructed volume, showing clearly where the particles are concentrated. In our measurements we confined the particles to seeding the vortex ring fluid inside the piston.

**Volume Reconstruction:**

After applying the self-calibration method (skipped herein), the images are ready for the volume reconstruction to calculate the volumetric particle distribution in the 3D voxel space. The processing multiplicative operation “Fast MART” has been used to reconstruct the 3D particle distribution with 5 iterations. Figures 4.17 and 4.18 show the 3D distribution of particles’ intensities and z-profile for the reconstructed volume. Figure 4.18 shows that the average brightness of the reconstructed
Fig 4.18: plots showing the intensities profile in the z-direction through the reconstructed volume.

particles are quite uniform across the reconstructed volume. This can be expected as we are looking at shadows which are uniformly dark across the volume, which have subsequently been inverted. This compares well with the conventional laser-illuminated volume slices where the intensity of the particles will depend greatly on where they are within the laser sheet.

Figure 4.19 shows typical particle reconstructions, where each plane corresponds to a thickness of one voxel. The reconstruction we performed is 1035 planes deep in the z-direction. Each particle is observed in about 10 adjacent planes.
Figure 4.19: One reconstruction plane out of a total of 1035 adjacent planes. Keep in mind that the width into the board of this plane is only 1 voxel, whereas the total horizontal width of the upper image is about 6000 voxels.
3D Cross-Correlation:

At this step the 3D velocity vector field can be calculated from the reconstructed volume using the processing operation “Direct Correlation”. Initial pass of 256 X 256 pixels interrogation region with a 1:1 elliptical weighting is usually used and followed by two 128 X 128 passes with interrogation region overlap of 75%. This

![Figure 4.20](image-url)

**Figure 4.20**: Velocity vectors in a plane near the centerline of the vortex ring. This is one of 27 reconstructed Tomo-PIV planes. The absolute value of the vorticity out of the plane is plotted by the color field. The right side of the vortex has a clear rotation and higher vorticity near the center of the vortex. The vorticity is broken up around the core on the left side.
results in 27 adjacent velocity planes, where we have about 90 x 80 velocity vectors in each plane, giving a total of 90 x 80 x 27 = 194,000 fully 3-D velocity vectors.

Figure 4.20 shows a typical plane of velocities. The region on the right side outside the vortex, is so devoid of particles due to low illumination intensity that no reliable vectors were found there. It is instructive to compare the right side of the vortex in Figure 4.20 to that from the projected image in Figure 4.16, where no information can be extracted in that region.
Figure 4.22  Velocity information in the center-plane cut through the vortex. The color indicates the magnitude of the horizontal component of the velocity vector. Showing the outflow on top of the vortex, whereas on the bottom the flow is towards the centerline.
Figure 4.23: The color indicates the magnitude of the vertical component of the velocity vector. It shows the up-flow near the center and on top of the vortex, whereas on the outer edges of the vortex flow are flowing downwards.

Figures 4.20 - 4.24 show some more results from this velocity volume.
Figure 4.24: The out of plane velocity in a plane near the edge of the vortex. The red color shows the top of the vortex coming towards us, with the bottom going into the board. This is consistent with predominantly out of plane motions near the edge of the vortex.

The three-dimensional nature of the velocity field is clearly demonstrated by the out-of-plane component shown in Figure 4.24. Here a plane cuts through the edge of the vortex, so the top flow is coming towards us and the bottom is going into the board.
4.2 Using Red and Blue LEDs:

Near the end of the work on this thesis, the difficulty of separating the Red and Green shadows became very apparent, as there was a lot of cross-talk between the colors. To try to fix this we therefore attempted some experiments with Red and Blue flashes, which are better separated in the wavelength space and will therefore have less cross-talk between these two channels. This was only possible using one camera, due to time-constraints and LED availability. This worked considerably better and should be pursued in future work. Figure 4.25 shows a typical example. When the green LEDs were replaced by Blue, splitting was enhanced and the identification of particles positions has determined to be more feasible. Figure 4.26 illustrates these enhancements with main featured advantages as follows:

- Less overlap in spectral space
- Much clearer separation of color-layers
Figure 4.25: Subsection from a typical Red-Blue LED image. The width of this panel is 1544 px.
Figure 4.26: Another example of the colour separation using RED-BLUE LEDs. The large “particles” are bubbles which are attracted to the cores of the vortex ring. The Green channel shown in the middle is almost entirely dark.
Figure 4.27: The pdf of the RED and BLUE pixel intensities, as well as the intensities of the difference RED-BLUE (black curve). The arrows point at two prominent peaks which indicate the pixels of most of the particles, which would make them significantly easier to separate than the RED-GREEN images used earlier in this thesis.

Figure 4.27 shows the pdfs of the intensities of the Red, Blue and their difference, calculated from the image in Figure 4.25. There are clear peaks on both sides of the zero value, representing the particles. There is an additional peak at positive difference, which is due to uneven background intensities, which have not been subtracted in this case.
Figure 4.28: Subsection of the previous figure, showing the individual color channels. The width of each panel is 784 px.

Figure 4.26 and 4.28 shows another example for the Red/Blue LED illumination. In this case the vortex ring has trapped a number of medium-size bubbles along its core. These bubbles are each close to spherical, as they are of the order of a millimeter, which is smaller than the capillary length in water, which is 2.7 mm. The capillary length characterizes the size where the buoyancy and surface tension are balanced.

The color of the bubbles are quite distinct, showing their motion between the flashes. It is nice to see the fully dark region where the two images of the bubble overlap. Figure 4.29 shows another realization where the bubbles are larger and aligned along the vortex core.
Figure 4.29: Image using Red/Blue LEDs. Shows an image subsection with a vortex ring with numerous large bubbles around the core of the ring. The bubbles are attracted to the core, by the low Bernoulli pressure there.

These bubbles are moving up with the translation of the vortex ring, while the outermost bubbles, at left of image, are shown to move downwards due to the vertical motions. This is of course not what such an image should be used for, as it represents a projection of many particles at different depth into the board, but for this case we only had an image from this one direction.

Figure 4.30 shows the intensity cut through two particle shadows, demonstrating a clear separation of the two pulses. This should be compared to the cut in Figure 4.5, for the red/green LEDs, now showing a much better result, which should be used in further experiments with this Tomo-PIV method.
Fig 4.30: photos and plots for Red and Blue LEDs experiment.
CHAPTER 5

Discussion and Conclusions

The work presented in this thesis provides an evaluation of a low-cost colored shadow imaging method for conducting tomographic PIV measurements. This new method is based on using two different color LEDs for the illumination and four commercial DSLR CMOS cameras for the imaging. The two different pulse-times were encoded in the images using two different colors (red and green) from the LED pulses. Two different experimental setups were used, to try to reduce optical distortions. As anticipated, the highest quality images were obtained with 8 LEDs (Tank-B model) to illuminate the volume, i.e. by using 4 pairs of two LEDs one for each color and where the pulse from each of these pairs of LEDs was directed toward a diffuser screen opposite to each camera. Different particle-seeding mechanisms were implemented, while a large pulse-driven vortex ring formed a flow patterns that allowed for the successful tomographic PIV measurement presented herein.

The processing was carried out by transferring the images manually to the Davis commercial software from LaVision (Germany). The color images were converted and split up into the red and green images using localized background subtraction and differences in the Red and Green channels. Following this we could successfully reconstruct two separate particles fields, corresponding to the
two different illumination times, thereby allowing for cross-correlations to get the three-dimensional velocity field.

In conclusion, we were able to perform a proof-of-concept realization using red/green LED illuminations. However, this demonstrated excessive cross-talk between the red and green channels on the sensor, due to overlapping sensitivities on the green wavelengths, into the red component. Finally, this result compelled us to try red/blue LED illumination, where the different color pixels are fully separated, which gave much better results for a single camera. This suggests that using red and blue LEDs shadows could give higher-quality Tomo-PIV results. This shows great promise, but will have to wait for future work.
REFERENCES


