Laser characteristics and configurations for high quality PIV measurements

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Abstract

The study of fluids and their behaviour has enabled society’s exploitation of wind and water flows for centuries. This field remains an area of active research, and furthering our understanding of turbulent fluid flows is particularly crucial to solving many of today’s engineering challenges. Improving car and aircraft fuel economy by decreasing aerodynamic drag, and optimising the efficient extraction of wind energy for electricity generation all demand a comprehensive understanding of turbulent flow mechanics. While many advanced computation tools are routinely used to model and study the behaviour of fluid flows, physical experimentation is often required when investigating complex real-world flow scenarios.

Particle image velocimetry (PIV) is one common laser-based experimental flow visualisation technique, which involves capturing at least two sequential camera exposures of illuminated flow-tracing particles in a region of interest. By estimating the displacement of these particles, a velocity field can be calculated and the behaviour of the flow can be analysed. However, noise in the experimental correlation of PIV data can degrade the quality of results and restrict the scope and complexity of a measurement campaign. This thesis investigates systematic methods for minimising experimental error sources, even before the capture of any PIV image pairs. By refining the experimental setup prior to performing PIV measurements, more accurate, higher quality data can then be fed into processing algorithms.

Non-ideal characteristics of a PIV measurement’s laser system, such as laser dynamic and transient behaviours, as well as light sheet intensity mismatch effects, are shown to have significant impacts on the performance of an experiment. Minimising and controlling these error sources, by applying careful adjustments to laser intensity profiles and operating procedures can greatly improve the quality of results. Diagnostic techniques and correctional procedures to account for these scenarios are rigorously discussed in this study.

Additional reductions in relative measurement error can also be achieved by increasing the data captured in an experiment using multipulse PIV, where a longer burst of sequential PIV images can be recorded to better filter noisy data. An analysis and comparison of this multipulse configuration assesses the relative benefits of this more
complex PIV technique. An overall assessment of the studied PIV error reduction methods is presented, to determine which approaches offer the greatest experimental performance.
Declaration of Authorship

This is to certify that:

- this thesis comprises only my original work towards the Doctor of Philosophy, except where indicated,
- due acknowledgement has been made in the text to all other material used,
- this thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Kristian J. Grayson

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<td>CCD</td>
<td>Charge-Coupled Device (image sensor)</td>
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<td>CID</td>
<td>Charge Injection Device (image sensor)</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide-Semiconductor (image sensor)</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
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<td>DEHS</td>
<td>Di-Ethyl-Hexyl-Sebacate (seeding fluid)</td>
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<td>DNS</td>
<td>Direct Numerical Simulation</td>
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<td>DSLR</td>
<td>Digital Single-Lens Reflex</td>
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<td>FTC</td>
<td>Fluid Trajectory Correlation</td>
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<td>GPU</td>
<td>Graphics Processing Unit</td>
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<td>OPO</td>
<td>Optical Parametric Oscillator</td>
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<td>PIV</td>
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<td>USB</td>
<td>Universal Serial Bus</td>
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</tbody>
</table>
Symbols

- \( \overline{\cdot} \) averaging
+ \( + \) viscous scale
\( ' \) fluctuation

\((r_x, r_y)\) generalised horizontal and vertical dimensions
\((x, y, z)\) streamwise, spanwise, and wall-normal coordinates
\((u, v, w)\) streamwise, spanwise, and wall-normal velocities

d laser beam diameter
\( F_O \) out-of-plane loss-of-pairs parameter
\( I_0(z) \) light sheet intensity profile
\( I_{max} \) maximum light sheet profile intensity
\( N \) Gaussian index
\( N_{ppp} \) particle seeding density
\( n \) pyramid correlation level
\( n_h \) local pyramid correlation height
\( R \) cross-correlation coefficient
\( Re_\theta \) Reynolds number based on momentum thickness
\( Re_\tau \) friction Reynolds number
\( T \) temperature
\( t \) time duration
\( \Delta T \) total PIV measurement time interval (time between the first to last laser pulses)
\( \Delta t \) PIV inter-laser pulse time interval (time between each laser pulse)
\( U_\tau \) friction velocity
\( U_\infty \) freestream velocity
\( z \)  
light sheet-normal dimension (also the wall-normal coordinate)

\( z_0 \)  
light sheet profile midpoint/centre

\( \Delta z \)  
out-of-plane particle displacement

\( \alpha \)  
angular displacement

\( \gamma \)  
gamma correction factor (for camera image processing)

\( \delta \)  
displacement

\( \delta_{max} \)  
maximum displacement

\( \epsilon \)  
relative error

\( \nu \)  
kinematic viscosity of a fluid

\( \sigma \)  
standard deviation of light sheet intensity profile
List of Publications

Journal Publications


Conference proceedings and presentations


Chapter 1

Introduction

1.1 Overview

Humanity has held an interest in fluids and their behaviour for centuries, where curiosity and necessity have prompted studies to manipulate and exploit the power of fluid flows. The development of waterwheels and mills, for example, extracted energy from flowing water to increase agricultural productivity using pumped irrigation, and generated mechanical power to aid production and manufacturing processes (Reynolds, 2002). Systematic, documented studies of fluid behaviours date back to the work of Archimedes and his text, “On Floating Bodies, Book I” (c. 250 BC), where he developed our understanding of buoyancy and fundamental fluid dynamics.

Figure 1.1: Turbulent water flow sketches by Leonardo da Vinci
Chapter 1. *Introduction*

The turbulent, chaotic nature of some fluid flows has also been the subject of investigations for many years. Leonardo da Vinci performed a number of studies examining fluid behaviour and produced numerous sketches depicting the multi-scale flows in turbulent wakes and falling streams of water (cropped samples of some of these sketches are shown in figure 1.1). These drawings show the eddies and vortices of water flows with impressive detail, across a variety of obstacle geometries and flow velocities. The recognition of turbulent flow behaviour appears to have even influenced early impressionist artwork, and in particular some of the work by Vincent van Gogh. Not only do works like “The Starry Night” (shown in figure 1.2) exhibit swirling, turbulent patterns, a study investigating van Gogh’s works suggest that the probability density function of luminance fluctuations even mirror Kolmogorov’s velocity distribution of turbulent flows (Aragón et al., 2008).

Present day studies of turbulence now investigate the detailed behaviour and manipulation of turbulent flows, crucial to solving many current engineering challenges. Examples of such challenges include improving car and aircraft fuel economy by decreasing aerodynamic drag, and optimising the efficient extraction of wind energy for electricity generation. Research into the behaviour of turbulent boundary layers, the chaotic thin layer of fluid that exists due to the relative velocity between a surface and fluid flow, is a key element in the understanding of turbulence and its application to engineering scenarios.

Many advanced computation tools are routinely used to model and study the behaviour of fluid flows, however complex real-world flow scenarios often require physical experimentation. While experimental measurements have been traditionally captured at discrete points within the flow, recent decades of development in flow measurement
techniques have introduced means of capturing large scale flow field measurements of planes and volumes of interest.

Particle image velocimetry (PIV) is one such non-intrusive flow technique that is frequently used to capture large, near-instantaneous velocity fields in which turbulent flow behaviour can be analysed. This non-intrusive approach contrasts with other common measurement techniques such as hot wire anemometry, where the insertion of the hot wire probe into the flow disturbs fluid behaviour downstream of the measurement location and limits the scope for simultaneous measurement configurations. Laser Doppler velocimetry offers a combination of these two approaches, using lasers to record non-intrusive point measurements. Therefore, while PIV trades large spatial measurement regions over temporal resolution, hot wire anemometry and laser Doppler velocimetry prioritise temporal performance at point measurement locations (see table 1.1 for a summary).

<table>
<thead>
<tr>
<th>Technique</th>
<th>Measurement Type</th>
<th>Temporal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle image velocimetry</td>
<td>Plane/Volume</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Laser Doppler velocimetry</td>
<td>Point</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Hot wire anemometry</td>
<td>Point</td>
<td>High</td>
</tr>
</tbody>
</table>

The popularity of PIV has increased rapidly in recent years since its initial evolution in the 1970s and 1980s (Pickering and Halliwell, 1984, Adrian, 1984, 1991), and is now recognised as one of the most popular means of measuring flow velocities. Figure 1.3 indicates the relative occurrence of references to different flow velocity measurement techniques in print sources between 1952 and 2008, using the Google Ngram dataset. Inspired by a similar plot originally shown in the Westerweel et al. (2013) review paper, this figure illustrates the rapid rise in the use of the PIV technique within the last 20 years, and its establishment as a central method of flow visualisation in the study of fluid dynamics.

The evolution of the PIV technique has allowed increasingly sophisticated high resolution and large field of view measurements to be undertaken, which offer deeper insights into flow physics and engineering applications. However, noise in the experimental correlation of PIV data can restrict the scope of such ambitious PIV measurement campaigns. Despite numerous works to-date seeking to address this challenge, many of the recent developments in 2D, planar PIV have not resulted from improvements to the quality of the measurements themselves, but from the evolution of correlation processing algorithms, which have increased robustness to noisy experimental data and reduced processing artefacts. This thesis seeks to return to the root cause of
many sources of PIV measurement errors, investigating systematic methods of mini-
mising experimental error sources, even before the capture of any PIV image pairs.
By refining the experimental setup prior to performing PIV measurements, higher
quality data can then be fed into the processing algorithms. Two key aspects of the
experimental process are considered in the reduction of PIV measurement errors and
correlation noise:

1. **Minimising and controlling experimental error sources**
   Limiting the introduction of experimental errors into PIV measurements due to
   non-ideal laser characteristics by applying careful adjustments to laser intensity
   profiles and operating procedures.

2. **Increasing data capture for error reduction**
   Additional reduction in relative measurement error can be achieved with the
   application of multipulse PIV (which involves a greater number of sequential
   PIV images than the conventional two-image pair) for the filtering of noisy data.

This thesis also restricts its focus to the use of 2D, planar PIV measurements conducted
in turbulent boundary layers and channel flows. However, many of the results from
this work can be equally applied to other fluid flows, stereo and tomographic PIV
methods, and potentially other laser-based flow measurement techniques.
Chapter 1. Introduction

1.2 Thesis outline

Chapter 2 provides a summary of the PIV technique, in addition to key developments in noise and error reduction. Prior works relating to the particular error minimisation approaches extended in this thesis are outlined, including previous applications of laser profiling and multipulse PIV techniques.

Many of the error sources considered in this study are investigated, at least in part, through the use of synthetic PIV image simulations. These PIV simulations offer a systematic and repeatable means of isolating variables within a PIV experiment for further analysis. The in-house simulation software and associated PIV processing code used throughout this study is the subject of Chapter 3. While the fundamentals of this software package were established by earlier contributions from the research group, extensive enhancements were made throughout this project to increase the fidelity of the simulated PIV images. These changes were to better reflect the imperfections routinely observed in laboratory PIV images – additions which are crucial to the investigations outlined in this thesis.

1.2.1 Minimising and controlling experimental error sources

The key error sources investigated in this work all relate to non-ideal behaviours of the PIV laser system. However, identification of these error sources due to laser operation requires a robust and repeatable means of quantifying laser performance. Chapter 4 outlines the design of an inexpensive laser profiling camera used throughout this thesis for measuring laser intensity profile characteristics. A performance analysis of the device is presented, with validation against established laser profiling methods.

Chapter 5 outlines the spectrum of diagnostic applications possible with regular use of a laser profiling camera, such as the design presented in Chapter 4. Uses can range from regular monitoring of laser performance to inform laser system servicing schedules, to directing optimisations of an experiment’s laser optic configuration.

The causes and consequences of laser transients and warm-up effects are addressed in Chapter 6, detailing laser warm-up behaviours and how they may disrupt an experimental measurement if ignored. The warm-up characteristics of single laser cavities, as well as potential coupled behaviours between the two cavities in a PIV laser are discussed. These results are synthesised into a series of recommendations for PIV experimentalists, which can limit the impact of such transient effects on PIV measurements.
Mismatch in the light sheet intensity profile of laser pulses, the subject of Chapter 7, can be a significant source of error and noise in PIV measurements. Variations in a light sheet’s width, shape and alignment can all impact out-of-plane loss-of-pairs, and can severely degrade correlation. A systematic analysis of this source of error is presented, including synthetic PIV simulations to quantify these effects, followed by experimental validation incorporating the laser profiling camera design from Chapter 4.

1.2.2 Increasing data capture for error reduction

Increasing the number of PIV images captured in sequence during an experiment can permit new possibilities for filtering measurement error. This additional data can either contribute to an average of the typical first-order velocity estimate calculated from conventional PIV measurements, or enable a higher order estimate of velocity. However, higher order velocity estimates will only ever achieve greater measurement accuracy if linear velocity estimates over measured timescales in the flow of interest do not sufficiently resolve motion. Chapter 8 discusses the impact of this linear approximation inherent in non-time resolved PIV measurements of boundary layer and channel flows. The results from this analysis therefore inform the conditions under which a higher-order velocity estimate may offer improved measurement accuracy.

Chapter 9 utilises the earlier results from this thesis to ultimately assess the value and potential of multipulse (four pulse) PIV configurations for the reduction of measurement errors. Alternative correlation processing approaches are discussed and these scenarios are compared. The relative gains of these multipulse approaches are assessed against the additional complexities involved, particularly the compounding impact of laser mismatch effects in multipulse measurements.
Chapter 2

Literature review

This literature review is intended to provide a brief overview of the particle image velocimetry approach and its development, with an emphasis on details which directly relate to the discussions contained within this thesis. Additional literature pertaining to laser profiling, transients, light sheet mismatch and multipulse PIV will be covered in the relevant chapters (Chapters 4, 6, 7, and 9, respectively).

2.1 The PIV technique

Over more than thirty years of development, particle image velocimetry (PIV) has evolved into an important and widely-used means of performing near-instantaneous and non-intrusive flow visualisation measurements (see the review article by Westerweel et al., 2013). This technique originated from more established laser speckle velocimetry methods, which have been used in solid mechanics, and later fluid flow investigations (Barker and Fourney, 1977, Grousson and Mallick, 1977, Dudderar and Simpkins, 1977, Adrian, 2005). Particle image velocimetry was distinguished as a method which captures discrete particle images, rather than densely overlapping particle speckle patterns, and was first described as such in the literature by Adrian (1984).

Fundamentally, this technique involves seeding the fluid flow of interest with particle tracers capable of following the dynamic behaviour of the flow with negligible interaction (Raffel et al., 2007, Adrian and Westerweel, 2011). These particles are illuminated by a high intensity light source, such that they can be imaged by a camera directed at the desired measurement field of view (see figure 2.1). At least two images are captured in succession, separated by a time delay ($\Delta t$) sufficient to observe the
motion of particles within the camera frame. Two pulse PIV is common, although multiple pulse bursts can be used (multipulse PIV), and long sequences of successive images can provide temporal flow information (time resolved PIV). Cross-correlation analysis of the captured images produce estimates of the particle displacement, and using the known light pulse delay, the flow velocity can be calculated.

A variety of different PIV configurations can be implemented, depending on the number of flow components required by the measurement. The most common and basic method is planar PIV, which uses a thin sheet of laser light to capture two components of fluid motion over a plane, with a camera oriented normal to the measurement plane (shown also in figure 2.1). Other techniques include stereographic PIV, which involves two inclined cameras focused on the same measurement plane, and is capable of extracting all three components of fluid motion in that plane (Prasad, 2000). More recent tomographic PIV techniques require the illumination of a volume of interest, where multiple cameras from different perspectives allow the three-dimensional volumetric reconstruction of flow velocities (Elsinga et al., 2006a, Scarano, 2013). Numerous other variations in PIV configuration exist, however the planar PIV method is the focus of investigations discussed within this thesis.

Early measurements with the PIV technique used film cameras, continuous lasers and optical Fourier transforms using Young’s fringes for displacement analysis (Raffel et al., 2007, Adrian and Westerweel, 2011). Modern PIV methods now use more sophisticated digital cameras (which capture exposures from each laser pulse individually), high
power pulsed laser systems, and computer-based cross-correlation techniques. Flow seeding typically consists of hollow glass spheres in water flows, and fine chemical or oil sprays (such as di-ethyl-hexyl-sebacate, better known as DEHS) are common in gaseous flows (Raffel et al., 2007).

2.1.1 PIV cameras

Modern PIV cameras generally use charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) sensors, capable of capturing at least two consecutive images with a minimal separation time. A “frame straddling” technique is often used to minimise the possible delay between successive PIV images, timing the first laser pulse at the end of the camera’s first exposure, and the second laser pulse at the beginning of the second exposure (Wernet, 1991, Lecordier et al., 1994). This configuration is also shown schematically in figure 2.2.

2.1.2 PIV illumination systems

High power pulsed laser systems are common in PIV measurements to freeze particle motion, precisely control image exposure, and achieve the necessary illumination intensity. Nd:YAG (neodymium-doped yttrium aluminium garnet) laser systems are widespread in two pulse and multipulse PIV measurements, typically in a frequency-doubled configuration to produce visible 532 nm light output (Raffel et al., 2007, Adrian and Westerweel, 2011). The laser pulse intervals demanded in many PIV experiments are too short for successive pulses from single cavity Nd:YAG systems, therefore PIV lasers usually consist of two laser cavities (one for each laser pulse), with beam combining optics for co-alignment of each beam (shown schematically in figure 2.3). Two timing signals are required for the operation of each laser cavity (see figure 2.4), first triggering the flashlamp, which excites the system and builds the energy within the laser cavity (2 in figure 2.3), followed by the Q-switch, which allows the energy release in a concentrated pulse using an electro-optical device known as a Pockels cell (1 in figure 2.3). An optimal delay exists between flashlamp and
Figure 2.3: A simplified internal schematic of a dual-cavity Q-switch pulsed 532 nm PIV laser system. The key components include the Pockels cells (1), pump cavities (2), two way mirrors (3) and (5), the harmonic generator (4), and a beam dump (6). The unannotated black plates represent standard laser mirrors.

Figure 2.4: Operation sequence for a Q-switch pulsed laser (reproduced from Adrian and Westerweel, 2011)

Q-switch triggering to enable maximum laser energy output. Repetition rates of these systems are typically 10-15 Hz, with laser pulse energies in excess of 400 mJ/pulse.

After emission from the laser system, the laser beam is manipulated by a series of optics to control the illumination of the measurement field of view. In planar and stereoscopic PIV, a thin laser light sheet is required to isolate particles, which is generated using a combination of negative and positive focal length optics (Raffel et al., 2007, Adrian and Westerweel, 2011).
2.1.3 PIV image processing

Basic PIV image processing is performed by dividing PIV images into smaller regions, or interrogation windows, which are cross-correlated and processed separately (see figure 2.5). A normalised cross-correlation scheme (Raffel et al., 2007, Adrian and Westerweel, 2011) is applied to each interrogation window, and the particle displacement is estimated using the shift in the correlation peak from the centre of the window, as shown in figure 2.6. After the displacement of each interrogation window has been estimated, these values are spatially recompiled to produce an array of velocity vectors describing the measured flow.

2.2 Developments in processing algorithms

Many of the key developments in PIV to-date have come from improvements to the algorithms processing experimental data, and numerous enhancements to the way processing algorithms handle PIV data have resulted in dramatic improvements to the quality of PIV results.
The treatment of PIV image interrogation windows was an area of early development, where iterative correlation schemes enabled the progressive refinement of displacement estimates and increases to the spatial resolution of results. The multipass method applies an iterative correlation procedure, whereby displacement estimates from earlier correlation iterations determine integer window offsets to one (or both) of the images in a PIV image pair during subsequent correlation “passes”. This method was first implemented by establishing window offset estimates for the second image using a forward differencing interrogation scheme (Westerweel et al., 1997), seen in figure 2.7a. A central differencing interrogation technique was later introduced (Wereley and Meinhart, 2001), shown in figure 2.7b, applying a symmetric window offsets in both the first and second images. The introduction of the so-called multigrid approach further leveraged the iterative correlation passes to enable progressive refinement of the interrogation grid to smaller interrogation window sizes, increasing spatial resolution (Scarano and Riethmüller, 1999, Gui and Wereley, 2002). This technique bypassed prior limitations on final interrogation window size due to large relative particle displacements. Window and image deformation schemes extended these techniques with sub-pixel deformation of a PIV image to correct for local velocity gradients. This approach was first proposed by Huang et al. (1993a,b), and developed in the works of Jambunathan et al. (1995) and Scarano (2001).

Further improvements to the performance of each interrogation window correlation has been achieved with the application of sub-pixel correlation peak detection using a functional fit, commonly a three-point Gaussian (Willert and Gharib, 1991, Raffel et al., 2007). Interrogation window weighting was also shown to increase correlation quality by reducing biasing and aliasing effects (Nogueira et al., 1999, 2001, 2002, Gui et al., 2000, 2001, Eckstein and Vlachos, 2009). Additionally, the Correlation Error Correction technique introduced by Hart (2000a,b) applies small shifts to interrogation windows, and resulting correlations are combined using element-wise multiplication.
This method suppresses random errors and further boosts correlation signal-to-noise ratios, thereby enabling smaller interrogation windows to be used in PIV processing.

The evolution in pre- and post-processing methodologies has also led to increased performance and robustness of PIV measurements. Image pre-processing procedures such as background subtraction from an averaged image (Raffel et al., 2007), histogram stretching (Adrian and Westerweel, 2011) and min/max filter contrast normalisation (Westerweel, 1993) have become commonplace in PIV experiments. Outlier detection techniques, such as the normalised median test (Westerweel and Scarano, 2005), are also extremely important for robust spurious vector detection and omission from output velocity fields.

2.3 Developments in the setup of a PIV experiment

In contrast with the attention given to PIV algorithm development, far less progress has been made in the refinement of PIV experiment setups for improved measurement performance. While this in part reflects the limited maturity of PIV algorithm development during the early years of the technique, several areas of improvement in the setup of an experimental remain worthy of deeper investigation to improve measurement quality.

2.3.1 Examining laser characteristics

The intensity distribution and alignment characteristics of the laser beam can have numerous impacts on measurement signal-to-noise and error performance. Laser burn papers and Polaroid pack film have been a common means of checking laser beam profiles, and this method has been applied in many studies, such as the work of Ganapathisubramani et al. (2005). Imaging a surface illuminated by a laser, either normal to the beam (Fond et al., 2015), or on an inclined surface for increased resolution (Kähler and Kompenhans, 2000, Mistry and Dawson, 2014), can also offer more detailed insights into a laser’s characteristics. However in recent times, electronic laser profiling techniques have become an increasingly practical and widespread tool for systematic, quantitative analysis of laser behaviour.

Electronic knife edge and slit profilers scan across the laser beam, isolating and measuring a thin slice of the laser at any one time. Each slice is then recompiled to generate a complete profile of the laser. Although this method can be more difficult to use with pulsed laser systems and cannot easily capture dynamic laser behaviours, it has been used to aid some PIV measurements (Mullin and Dahm, 2005).
Camera based laser profiling methods allow the entire laser beam to be captured simultaneously, and this method is more commonly used in PIV measurements to examine the intensity distribution and alignment of laser beams and light sheets. This type of device was also used by Mullin and Dahm (2005), as well as in turbulent premixed flame measurements by Pfadler et al. (2009) and a turbulent jet flow study by Naka et al. (2016). The value of a readily available, lower cost alternative to these diagnostic devices has also been demonstrated, following testing of webcams for laser profiling applications with other laser-based measurement techniques (Cignoli et al., 2004, Andrébe et al., 2011, Langer et al., 2013). These diagnostic tools enable detailed examination of laser characteristics throughout the beam path, to infer and tune laser behaviour for optimal PIV results, and are the subject of discussion in Chapters 4 and 5. These devices are also extensively applied in the analyses on laser transients in Chapter 6, and laser light sheet mismatch in Chapter 7.

2.3.2 Use of multipulse PIV

The implementation of a multipulse PIV setup captures additional PIV images to increase the information on a given flow, which may be exploited to enhance flow measurement quality and reduce experimental errors. This approach was originally developed using autocorrelation or Young’s fringe analysis (an optical PIV processing method using optical Fourier transforms), and is outlined in a thorough discussion by Keane and Adrian (1991). Despite there being a number of variations to multipulse PIV, not all configurations use this additional information for minimising measurement errors.

Multiple pulses in a PIV experiment have been used to simultaneously examine multiple adjacent measurement planes in a number of PIV investigations (where two laser pulses may align along plane A, and a further two pulses illuminate the nearby plane B, for example). This multiple plane PIV arrangement was introduced by Kähler and Kompenhans (2000), who proposed a variety of polarisation-separated spatial and temporal plane stereo PIV configurations for studying in-plane and out-of-plane flows. This methodology has been applied to several experiments, such as the examination of two spatially separated measurement planes in the four pulse stereo PIV studies of Mullin and Dahm (2005) and Pfadler et al. (2009). Ganapathisubramani et al. (2005) also performed a spatially separated dual plane, four pulse PIV measurement, which applied stereo PIV in one plane of measurement, and planar PIV in the other. Furthermore, eight pulse stereo PIV studies capturing four adjacent measurement planes have been performed by Kerl et al. (2013) and by Naka et al. (2016), in flame and turbulence studies, respectively. However, in each of these experimental examples,
as with standard two pulse PIV measurements, each distinct measurement plane only receives two laser pulses for the estimation of velocities.

Multiple sequential pulses of coincident laser light sheets (ie: on the same measurement plane) are used in multiframe PIV measurements, outlined by Hain and Kähler (2007). This arrangement improves dynamic velocity range and reduces measurement error by locally pairing PIV images at different inter-pulse time intervals, $\Delta t$, to optimise the local correlation coefficient and signal-to-noise ratio. For example, even if large velocity variations exist within the measurement field of view, laser timing may be tuned for sufficient particle displacements with a 1-2 image pairing (ie: cross-correlation of the first and second images from the image sequence) throughout the bulk of the experimental domain. Meanwhile, regions with lower flow velocities and smaller particle displacements, near a wall for example, will produce poor results with the same 1-2 image pairing. Using the multiframe algorithm, the additional laser pulses captured in the experiment can enable 1-3 or 1-4 image pairings (ie: using the first and third, or first and fourth images for cross-correlation), which involve greater particle displacements, to be locally applied to these low velocity regions in the field of view. In the Hain and Kähler (2007) study, this method was applied to a DNS PIV simulation of a laminar separation bubble flow and an experimental aerofoil flow using planar PIV. Persoons and O’Donovan (2010) also outline a similar multiframe configuration, which is validated by performing planar PIV measurements on an impinging jet flow. But note that while multiple pulses are used in these experiments, only two PIV images are applied to any velocity measurement. Similarly, four pulse experiments explicitly designed for material acceleration estimation in planar (Liu and Katz, 2006) and tomographic PIV configurations (Lynch and Scarano, 2014) use two images for each velocity calculation, and compare these velocity results to determine the flow’s acceleration. Therefore, a large amount of captured flow information is underutilised by these techniques during the processing of results by only considering two PIV images in isolation.

Comprehensive exploitation of the information obtained from coincident multipulse PIV measurements require modifications to the way images are correlated during results processing. Three pulse planar PIV, for example, was outlined by Farrugia et al. (1995) with a triple correlation algorithm. More advanced multipulse algorithms, capable of handling longer image sequences, have also been proposed and demonstrated with experimental data. These include the pyramid correlation (Sciacchitano et al., 2012), which considers all possible cross-correlation combinations from a multipulse image sequence, including image pairs over differing time intervals, to generate a pyramid-like set of correlation functions. To correct for time interval differences, cross-correlation functions originating from shorter intervals are dilated to a common
longer timescale, before the functions are averaged together and the displacement
peak is found. This technique was tested on the near wake of an aerofoil, as well as on
measurements of a circular water jet. Additionally, a pyramid-like correlation algorithm
has been applied to a single volume tomographic PIV measurement, involving four
temporally separated laser pulses, which examined the turbulent boundary layer flow
downstream of a backward facing step (Schröder et al., 2013). The fluid trajectory
correlation (Lynch and Scarano, 2013) also exploits sequences of PIV image data
by applying a best fit to the estimated trajectory of fluid parcels. This method was
tested on a transitional jet and has been extended for ensemble-averaged trajectory
estimates when mean flow characteristics are of interest (Jeon et al., 2014). Many
of these methods were originally developed for time resolved data sets, where long
image sequences are available. However some published results also show cases
using shorter image sequences consistent with multipulse PIV configurations. The
potential advantages of multipulse methods in modern PIV experiments have also
been discussed by Westerweel et al. (2013), and a numerical study of multipulse
particle tracking performance has been presented by Ding et al. (2013), alongside
preliminary experimental validation using PIV measurements. These discussions were
extended in Ding and Adrian (2016), in which three and four pulse PIV (referred
to in this study as N-pulse PIV) were considered for flow velocity and acceleration
measurements over an oscillating cylinder. Yet further characterisation of correlation
algorithm performance is needed to understand the current benefits of multipulse PIV
(particularly for wall-bound turbulent flows), relative to conventional two pulse,
planar PIV. An assessment of these advantages and trade-offs is the subject of further
analysis and discussion in Chapter 9.
Chapter 3

PIV processing and simulation software


Systematic investigations of the impact errors have on PIV experiments can be extremely challenging to perform in the laboratory, since measurement variables are difficult to test in isolation. Generating synthetic PIV image pairs, using specially designed software, enables precise control over experimental variables for the detailed, repeatable examination of PIV error effects. This degree of control over PIV variables is essential to many of the analyses presented in this thesis, such as the discussions found in Chapters 7 and 9.

The PIV synthetic image generation and correlation processing code used in these studies is an in-house MATLAB-based software package, developed within the University of Melbourne Fluids Group. Compared with the “black box” encountered in commercially developed PIV processing suites, this internally-developed software package enables far greater control over the processing of data, as well as allowing users to implement their own modifications and enhancements to the code. It was first established during the PhD research of Charitha M. de Silva for tomographic PIV processing (de Silva et al., 2012, de Silva, 2014), and has continued to develop, undergoing enhancements for 2D PIV analysis, in addition to new processing algorithm features. Both synthetic and experimental PIV data sets can be handled by the package.
In this thesis, the primary use of the software package is to isolate and systematically investigate the sensitivity of various error sources on the quality and accuracy of PIV measurement results. The synthetic image generation procedure in this software had only been developed for basic analysis of PIV processing algorithms, and in particular, tomographic PIV reconstruction techniques (de Silva et al., 2012, de Silva, 2014). Only simplified synthetic images were required for these prior studies, which did not reflect many of the error sources encountered in real-world PIV experiments and images. For the purposes of the investigations in this thesis therefore, a number of enhancements were necessary, particularly relating to the synthetic image generation code. However, before the details of these modifications are outlined, an overview of the existing software’s features and structure is necessary.

3.1 Existing PIV package

This MATLAB-based PIV synthetic image generation and correlation code was designed to utilise a computer’s multi-core central processing unit (CPU) and also, if available, the graphical processing unit (GPU). Synthetic images are generated by modelling randomly located three-dimensional particle spheres within the simulation volume, which are illuminated along the light sheet plane. The illuminated spheres are rendered from a virtual camera perspective to create the synthetic PIV images. These spheres are then displaced according to the input fluid flow velocities, which are typically defined by direct numerical simulation (DNS), or artificial flow fields.

The PIV processing element of the code consists of the following key features:

- A range of image pre-processing options, including histogram thresholding, background subtraction, and image intensity normalisation
- 2D and 3D calibration processing for PIV data
- Multiplicative Line of Sight (MLOS) based reconstruction for tomographic PIV data sets
- Cross correlation featuring multi-pass, multi-grid, and image deformation algorithms, with Gaussian correlation peak fitting for sub-pixel displacement estimation
3.1.1 Package structure

The PIV package is separated into two distinct program files, shown schematically in the figure 3.1 flow chart. The Run Parameter Code file defines the configuration settings used in the processing procedure, and is therefore frequently modified by the user to handle different PIV simulations and experiments. The PIV Processing Code file contains the algorithms and sub-functions necessary to handle the PIV simulations or experimental images, according to the settings defined by the run parameters.

The PIV Processing Code file contains a number of components which allow it to handle both synthetic and experimental PIV data. A series of core processes are applied to most procedures, which include the calibration and correlation of PIV images. Synthetic PIV image generation can be considered a distinct element of this code, called only when simulated PIV measurements are to be synthesised and processed. Reconstruction of the particle images, either due to rescaling the images from the calibration data, or tomographic reconstruction for volumetric PIV techniques, can be considered another component which may be applied during experimental
and simulation processing. A number of the code’s processes are contained within sub-functions for modularity, indicated by the bold text in the figure 3.1 flow chart.

### 3.2 Assessing PIV image characteristics

The PIV error investigations in this thesis, such as the analyses in Chapters 7 and 9, require synthetic images with sufficient fidelity to replicate the important noise characteristics found in experimental PIV images. But to verify the noise characteristics of these synthetic images, methods of quantifying such behaviours are required.

Two key methods are applied in this work to measure the nature of particle images and pixel intensities within a PIV image. The first technique examines the average seeding particle radius by autocorrelating PIV image interrogation windows, and averaging the results. The radius can be estimated from the autocorrelation plot using a width criterion, such as when the autocorrelation magnitude falls below $1/e^2 = 0.135$. Outlined by Adrian and Westerweel (2011), this measure (see figure 3.2a) can not only examine the image’s particle radius, but the gradient of the peak edges also indicate the degree of variation in particle radius. The second technique investigates the distribution of pixel intensities throughout the PIV image, first used by Westerweel (2000). This plot (shown in figure 3.2b) assesses the maximum particle intensities, particle density, background noise, and image sharpness. With the aid of these tools, synthetic PIV images used in this thesis should ideally mirror the general characteristics found in experimental PIV image pairs.
3.3 Synthetic image generation code improvements

The code enhancements introduced for the work in this thesis focus on two key areas: improvements to the synthetic image generation procedure to better reflect the behaviours found in experimental PIV images, and the addition of advanced correlation algorithms capable of exploiting the additional data available in multipulse (three or four pulse) PIV measurements (outlined in Section 3.4 and further discussed in Chapter 9).

A number of major changes were made to the synthetic image generation process to include additional characteristics found in experimental PIV images, as well as to optimise the processing speed of the procedure. The existing synthetic image modelling method was a computationally intensive and time consuming process, where thousands of particle spheres required modelling and rendering in three dimensions throughout the simulation volume. Given the combination of extensive code changes required for this study, there was also an opportunity for radical changes to be made to the image generation approach, outlined below, to enhance both the fidelity and efficiency of the procedure. This extended functionality also introduces a number of additional image generation parameters. While the image parameter values used in this section were chosen for purely illustrative purposes, a procedure for matching these simulation parameters to an experimental data set is detailed in Section 3.5.

3.3.1 Simulation of particles beyond the light sheet

The original image generation code assumed that all simulated particles are fully illuminated by a uniform intensity (top hat profile) laser light sheet. But many subsequent changes to the code require only part of the defined simulation volume to be fully illuminated by the laser, such as when simulating the misalignment of two light sheet pulses. Consequently, separate parameters for the light sheet thickness and the simulation volume thickness were introduced, so that a particle’s illumination can vary based on its depth in the light sheet. This change allows out-of-plane particle motions to be fully modelled, in addition to producing dark, unilluminated particles which can potentially obscure illuminated particles in a PIV image (visible in the top of figure 3.3a).

3.3.2 Implementation of 2D Gaussian image generation

The existing 3D particle rendering approach produced visually acceptable PIV images which simplified the use of this code for multi-camera tomographic PIV simulations.
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However, the nature of this process in MATLAB restricts the control over many synthetic image parameters, such as limiting images to an 8-bit depth, compared with the 14-bit or 16-bit resolution of many PIV cameras. The appearance of particles in a synthetic image is also highly dependent on the lighting model and rendering settings applied in MATLAB – a Phong shading model is used in this code, which applies a sum of ambient, diffuse and specular reflection elements to depict a surface (Phong, 1975). All of these factors can combine to produce particle images with a much “flatter” appearance (see the top image in figure 3.3a) than what is observed in many experimental particle images. Furthermore, if the normalised pixel intensity distribution of the synthetic image is examined (see the bottom of figure 3.3a), clear discrepancies can be found when compared with the distribution from a sample experimental PIV image, shown by the grey line (reproduced from figure 3.2b). Particle images should exhibit more Gaussian-like light fall-off from the edges of illuminated particles, and control of these characteristics is not possible within the restrictive MATLAB 3D illumination functionality. It is also worthwhile noting that the experimental PIV image used to generate the grey lines in figure 3.3...
was chosen as a representative sample of results found in typical experiments at the University of Melbourne fluids laboratory, examining turbulent boundary layer air flows in wind tunnels with DEHS smoke particles (such as the measurements of de Silva et al., 2014, 2015).

An alternative synthetic image process was developed to model illuminated particles as two-dimensional Gaussian functions. Images are built up, particle by particle, as a two dimensional array, with a size equivalent to the pixel dimensions of the desired image. Perspective distortion is applied to the particle locations to achieve the correct relative positioning of particles in the image, and lens distortion options are available (for radial barrel/pincushion and tangential lens distortions). 8-bit or 16-bit images can be produced from this process, so that the dynamic range of PIV cameras can be better replicated. As images are simply 2D arrays, they can be easily processed and modified for additional functionality. Note that the unrealistic shadowing effects encountered using the 3D particle rendering technique are also removed in this 2D procedure (this difference can be observed when comparing the top of figures 3.3a and 3.3b). Obstruction from out-of-plane particles is not a behaviour typically observed in PIV images due to diffraction effects.

Table 3.1: Comparison of 2D and 3D synthetic image generation times

<table>
<thead>
<tr>
<th>Number of Simulation Particles</th>
<th>3D Image Generation Time</th>
<th>2D Image Generation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>155 seconds</td>
<td>0.13 seconds</td>
</tr>
<tr>
<td>20,000</td>
<td>3,346 seconds</td>
<td>0.18 seconds</td>
</tr>
</tbody>
</table>

The output from the 2D Gaussian image generation procedure is shown at the top of figure 3.3b. The normalised pixel intensity distribution at the bottom of figure 3.3b shows behaviour with greater similarities to experimental PIV images (the grey line) than results using 3D generated synthetic images. The 2D Gaussian synthetic image generation process is also significantly more computationally efficient than the 3D generation code, demonstrated by the comparison in time required to generate a single synthetic image on a standard desktop computer, shown in table 3.1. This duration covers only the time required to plot and save the synthetic image, and excludes the particle flow displacement routine common to both codes. While these computation times do vary with the simulation parameters, the distinct order of magnitude differences between the two image generation approaches remain. The speed advantages of the 2D image generation code enable direct simulations of 11 megapixel PIV camera images containing 2.5 million particles to be generated in under 8 seconds. However verification of the 2D image generation process has been restricted to the study of 2D, planar PIV simulations to date – further testing is
3.3.3 Non-uniform light sheets

The flexibility to apply user-defined light sheet intensity profiles was also introduced, so that light sheets are no longer restricted to uniform, top-hat intensity profiles. The light sheet intensity distribution scales the peak height of the 2D Gaussian representing each illuminated particle, based on the particle’s depth in the light sheet. Gaussian and super-Gaussian distributions are implemented (the latter is calculated using the conventional Gaussian formula, but where the content of the exponent is raised to a power greater than 2), as well the option to apply custom profiles such as those acquired from an experiment’s light sheet profile using a laser profiling camera (see Chapter 4). Furthermore, a different intensity distribution can be applied to each simulated laser pulse to model the variations observed between PIV laser cavities. A
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sample synthetic image using a Gaussian light sheet is shown at the top of figure 3.4a, and the normalised pixel intensity distribution shows a smoother and more realistic behaviour relative to figure 3.3b (and closer to the experimental grey line).

### 3.3.4 Background image noise

Functionality to model background image noise has been implemented to simulate camera shot and sensor noise, as well as background light. Three distinct noise settings can be controlled – normally distributed random noise defined by the mean and standard deviation of the distribution, uniformly distributed random noise limited by an upper noise threshold, and a fixed-offset noise floor. Figure 3.4b shows a synthetic image with aggressive normally distributed background noise for illustrative purposes. A clear peak is visible in the figure 3.4b normalised pixel intensity distribution, similar to the kind of peak observed in experimental PIV images (the grey line).

### 3.3.5 Particle size variations

PIV particles are rarely all identical in size, so functionality to vary the simulation particle size was introduced. Random normal distributions or uniform distributions of particle size can be applied to the simulation images by defining the standard deviation or range thresholds respectively. Separate horizontal and vertical particle radius variations can be applied, allowing for fixed circular or elliptical particle shapes to be generated. Figure 3.5b shows a sample simulation image containing particle variations, compared with the uniform particle sizes found in figure 3.5a. The impact of particle size variations can also be observed in the figure 3.5c plot of average particle radius characteristics, calculated by using autocorrelation across the image. However, note that in order to visually emphasise the changes in autocorrelation distribution, simulations with smaller particle diameters were used to generate the plot in figure 3.5c.

### 3.3.6 Radial blurring

Camera lenses typically do not provide uniform sharpness across an entire image – the greatest sharpness is common in the centre of the frame, decreasing out towards the image corners. In severe cases, this loss of sharpness can have a significant impact on image quality, distorting particle images and influencing an image pair’s correlation. Distortion or blurring of particles also increases their apparent particle diameter in a PIV image. Figure 3.6 compares the average particle radius characteristics in the
Chapter 3. *PIV processing and simulation software*

(A) 2D generated synthetic PIV image with Gaussian light sheet and image noise

(b) 2D generated synthetic PIV image with Gaussian light sheet, image noise and particle variation

(c) Comparison of average particle radius characteristics with fixed and variable particle sizes. Note that smaller particle diameters were used for the simulations in this plot, to graphically emphasise the impact of variable particle size on the autocorrelation distribution

**Figure 3.5:** 2D generated synthetic PIV image samples (including a Gaussian light sheet and image noise) with fixed and variable particle sizes

(c) Comparison of the average particle radius characteristics over an entire experimental PIV image, and over just the sharpest region of the image

**Figure 3.6:** Comparison of the average particle radius characteristics over an entire experimental PIV image, and over just the sharpest region of the image
sharpest region of an experimental PIV image, with the larger average radius found over the entire image. A radial blurring mask was implemented in the synthetic image generation code which allows the image corner loss of sharpness to be simulated. The radius and gradient of the mask can be specified to control the aggressiveness of the filter. Figure 3.7 compares two sample simulation images – with and without the application of the radial blurring filter, where light fall-off and larger, blurred particles can be observed towards the corners of figure 3.7b.

### 3.3.7 Light sheet misalignment

Dual-cavity laser systems are used in many PIV applications to enable sequential pulsing of the laser over very short time intervals. While the beams from these two laser cavities are typically combined within the laser system, they are not always found to be coaligned. Any offset in the alignment of these beams can also be observed in the light sheets generated by the laser, which can inadvertently illuminate different measurement regions and particles in the flow (see the schematic shown in figure 3.8). Such an effect is equivalent to an out-of-plane velocity component, causing a decrease in the proportion of imaged particles which can be paired in a PIV image set (ie: causing an out-of-plane loss of pairs) and thereby reducing the correlation quality of the measurement. The sensitivity of this misalignment is discussed in detail in Chapter 7.
Since this misalignment phenomenon is common (with varying severity) in experimental measurements, and a key contributor to measurement noise and errors, it is also an important behaviour to implement in the synthetic image generation code. To permit this functionality, further modifications enabled the out-of-plane location of each laser pulse to be defined independently. This typically requires the simulation volume to be thicker than each individual light sheet thickness, to account for the misalignment offset between the light sheets.

Imperfect laser behaviour can also produce irregular and unmatched variations in a light sheet's intensity distribution. These characteristics can be simulated by applying experimentally captured, non-uniform light sheet profiles, outlined in Section 3.3.3.

### 3.4 Correlation code improvements

Advanced correlation algorithms were also added to the processing code to enable the investigations into multipulse (three or four pulse) PIV techniques, discussed in Chapter 9. These correlation procedures aim to utilise the additional information available in three or four consecutive PIV images, as compared with the traditional two image pair, to reduce measurement errors and improve the resolution of the flow measurements. Changes to the PIV correlation sub-function (outlined in section 3.1.1) are necessary for these enhancements, and comprehensive details of these modifications are discussed in Chapter 9.
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### 3.5 Matching simulation parameters to experiments

The additional features introduced into the synthetic image generation code allow synthetic PIV image behaviours to be matched to a given experimental data set. This matching procedure requires a dark field image from the PIV camera used in the experiment, a captured PIV image data set from the desired experimental measurement, as well as profiles of the light sheet intensity distribution over the centre of the measurement field of view. Using this information, the following sequence is used to systematically match simulation variables to the experimental image behaviours:

1. Set the simulation’s image resolution and field of view to correspond with the experimental conditions that are to be matched.

2. Process the laser profiles from each laser pulse to extract the light sheet intensity distribution, rescaled to match the simulated volume dimensions. Apply these custom intensity distributions to the laser pulses in the simulation.

3. Plot the normalised pixel intensity distribution of a dark field image from the PIV camera used in the experiment. Perform a Gaussian fit to the low pixel intensity noise peak, recording the mean and standard deviation parameters – these values will be applied to the normally distributed background noise model in the synthetic image simulation. If any other notable image noise characteristics are observed (a significant number of dead or hot pixels, for example), record their properties for replication in the synthetic image code.

4. Extract a small region of a representative experimental PIV image, covering the sharpest part of the image (typically the centre). Compare the average particle radii using the interrogation window autocorrelation of this extracted region with the autocorrelation from the current simulation image. Iteratively tune the particle image diameter and diameter variation of the simulation to best match the experimental autocorrelation results.

5. Plot the pixel intensity distribution over the entirety of the same representative experimental PIV image, and compare to the simulation image. Use the un-normalised form of these plots to determine the maximum particle intensity to be applied in the simulation.

6. Assess the particle density of the images, and tune the particle count in the simulation with the aid of the normalised pixel intensity distribution. A visual comparison can also be instructive during this process.
Chapter 3. *PIV processing and simulation software*

7. Any additional unsimulated image noise characteristics observed in the normalised pixel intensity distribution can be identified and added to the simulation, if required. For example, to further match the location of the image noise peak or to align with the pixel intensity gradient, a small amount of additional uniform image noise may be added to shift the normalised pixel intensity distribution to slightly higher values.

8. Perform the interrogation window autocorrelation procedure over the entirety of the representative experimental image, comparing this result to that from the simulation. Discrepancies in the particle size distributions can be iteratively corrected by introducing a soft, gradual radial blurring to the image edges and tweaking the blur mask parameters. Visual comparison of the experiment and simulation corners can also be of use during this process.

Following the completion of this matching procedure, the autocorrelation and normalised pixel intensity distribution plots should display similar behaviour, such as the closely matched characteristics of a simulation and experiment shown in figure 3.9. In fact, the resulting synthetic image is also quite difficult to visually distinguish from the matched experimental image when compared side-by-side, as presented in figure 3.10.
Figure 3.10: Comparison of experimental PIV image and matched synthetic PIV image
Chapter 4

Laser profiling camera


Many sources of measurement error in PIV experiments arise due to the non-ideal behaviour of the experimental equipment. In particular, imperfect characteristics of lasers in PIV measurements can have impacts on captured data which can degrade the correlation of PIV image pairs. Each pulsed laser sheet in a PIV measurement must be well overlapped and aligned in order to achieve high quality PIV results. The uniformity and profile of laser beams are also known to drift from their initial specification over time, and may need adjustment with regular servicing. Identification and correction of these imperfections in laser behaviour therefore require a robust method of quantifying laser beam characteristics.

A variety of laser profiling techniques exist, and a repeatable, systematic and high resolution means of measuring laser profiles and light sheets can be a useful aid when preparing experimental setups and monitoring laser performance.

4.1 Overview of laser profiling techniques

4.1.1 Non-electronic profiling techniques

Burn tests are the most common means of verifying laser profiles and alignment in PIV, since they are quick to obtain and burn paper can be relatively inexpensive to procure. A variety of possible burn paper mediums exist for use to analyse laser profiles, and each has different burn characteristics and cost. However, detailed analysis of laser
profiles may be difficult using burn papers due to limited resolution and dynamic range – more sensitive electronic profiling methods are much better suited for this purpose.

Zap-It burn paper is purpose-made laser burn paper which offers moderate dynamic range for burn tests and claims sensitivity to energy densities between 5 mJ/cm\(^2\) and 20 J/cm\(^2\) (Zap-It Laser, 2016). In practice it does not respond to low energy and highly spread PIV laser beams, but otherwise offers a burn silhouette of higher power lasers (see a sample single-shot burn test of a 400 mJ/pulse beam in figure 4.1a).

Traditionally, Polaroid pack film was used for burn measurements (the peel-apart Polaroid pack film, rather than modern integral instant film), where previously developed film (that has been exposed in darkness) is placed in the path of a laser beam. This method has a relatively high sensitivity and dynamic range (see figure 4.1b for a single-shot burn test of a 400 mJ/pulse beam). However pack film products have recently been discontinued (such as Polaroid 667, Fuji FP-3000B and FP-100C films), so availability is now limited to a diminishing stockpile of film.

Coarse burn tests can also be made using light sensitive papers such as Kodak Linagraph Type 1895 paper for a burn silhouette. Crude, low sensitivity testing can even be performed using thermal paper found in cash registers and thermal printer-type fax machines.

### 4.1.2 Electronic profiling techniques

Electronic profiling methods offer a higher resolution means of analysing laser behaviours, but aggressive attenuation is needed for most sampled laser beams due to the sensitivity of the electrical componentry. Two distinct approaches have been used
to attenuate and capture laser cross sections, a scanning knife edge or slit method and camera based techniques.

Knife edge and slit profilers are electromechanical devices that scan the cross section of the laser with a slit or knife, which blocks the majority of incoming light from the profiling sensor. Small slices of the profile are measured sequentially across the beam and the complete profile is subsequently reconstructed. While good resolution can be achieved using this technique, it is only practical for analysing continuous laser beams and not the pulsed lasers frequently used in many PIV measurements. Dynamical behaviours of a laser beam are also more difficult to investigate using this method.

Camera based profiling techniques are of greater value for pulsed PIV laser analysis, since the entire profile of a single laser pulse can be captured simultaneously on the imaging sensor. Laser attenuation is also required to protect the sensitive imaging sensor from damage, which must be applied with a series of neutral density filters and/or beam splitting optics. Resolution is limited by the profiler’s sensor, which can be a Charge Injection Device (CID), Charge-Coupled Device (CCD) or Complementary Metal-Oxide-Semiconductor (CMOS) sensor design.

Dedicated camera-based laser profiling devices are available commercially from many scientific instrument and laser equipment suppliers (see figure 4.2 for some examples). However these products typically cost thousands of dollars and even then require the addition of light attenuating optics to reduce the energy density of profiles from lasers frequently used for PIV. Some of these products also lock researchers into using proprietary software packages to interface with the equipment, which can restrict user flexibility.

Alternatively researchers have, for several years, been successfully repurposing computer webcams for laser beam alignment and profiling (Cignoli et al., 2004, Andrèbe et al., 2011, Langer et al., 2013). This approach offers a low-cost, off-the-shelf solution to laser beam analysis that has been demonstrated in applications ranging from Laser...
Induced Fluorescence measurements to verifying laser alignments in experimental fusion reactors (Cignoli et al., 2004, Andrèbe et al., 2011). Since almost all webcams use a colour imaging sensor, additional information can also be extracted from the behaviour of the red-green-blue Bayer filter that covers the webcam’s sensor (Langer et al., 2013). The webcam only requires the removal of the lens and the addition of light attenuating optics to function. This lower-cost laser profiling approach is extended throughout the remainder of this chapter to better suit the profiling of relatively large-diameter PIV laser beams.

4.2 Profiling camera design

4.2.1 Design requirements and goals

Given the high cost and limitations of commercial laser profiling cameras, an opportunity exists for an inexpensive, modular, off-the-shelf alternative that offers flexible operation and interfacing options for users. The design of such a camera for profiling laser equipment used in PIV applications must feature the following minimum capabilities to be of practical use:

- Profile a laser beam and a laser sheet from a 532 nm Nd:YAG laser (a common laser used in PIV measurements)
- Capture beams up to 9 mm in diameter and with a variety of energies up to 400 mJ/pulse
- Record a single-shot profile with the laser running at a minimum of 1 Hz

In addition, the following performance goals were outlined for the camera design as desirable features:

1. A portable and compact system that can be quickly and easily configured in-situ for use with various experimental setups
2. Flexibility to be used with other wavelength lasers (primarily lasers with wavelengths within the visible spectrum)
3. Offer feedback on laser profiles with minimum delay (near real-time feedback)
4.2.2 Imaging configuration

While the USB webcams outlined by Cignoli et al. (2004) and Andrèbe et al. (2011) can be used on the lasers commonly found in PIV measurements, the imaging sensor size (typically approx. 3.2 mm × 2.4 mm) is insufficient to fully capture unfocused PIV laser beams (which are often 6 to 9 mm in diameter). Rolling shutter effects commonly observed in these types of sensors can further complicate the capture of pulsed laser profiles.

Digital photographic cameras offer many of the advantages of webcams, in addition to greater manual control and larger, higher resolution imaging sensors which easily accommodate typical PIV laser beams. A larger sensor size also allows for greater margin in camera alignment with the laser beam. Furthermore, digital camera images can typically be saved in raw, uncompressed formats, which can be important for any quantitative analysis of laser profiles. Since no lens is needed to profile a laser beam, an interchangeable lens camera body is preferable to a point-and-shoot style camera, which would otherwise require manual removal of the built-in lens assembly. Digital single lens reflex (DSLR) and mirrorless interchangeable-lens camera (MILC) bodies are well suited to this application, and are readily available through consumer camera retailers.

Both DSLR and MILC systems have been tested as laser profiling cameras with success, summarised in Table 4.1. Many of these cameras also offer the possibility for tethered shooting, where the camera is interfaced with a computer via USB while capturing images. The Nikon D5200 and D5600 camera bodies are capable of sustained capture of laser profiles at 1 Hz (the same frequency as the PIV cameras used for experiments in this laboratory).

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>Camera System</th>
<th>Sensor Size (mm)</th>
<th>Resolution (megapixels)</th>
<th>Image Size (pixels)</th>
<th>Pixel Density (pixels/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canon EOS-M</td>
<td>MILC</td>
<td>22.3 × 14.9</td>
<td>18</td>
<td>5184 × 3456</td>
<td>232</td>
</tr>
<tr>
<td>Nikon D5200</td>
<td>DSLR</td>
<td>23.5 × 15.6</td>
<td>24</td>
<td>6000 × 4000</td>
<td>255</td>
</tr>
<tr>
<td>Nikon D5600</td>
<td>DSLR</td>
<td>23.5 × 15.6</td>
<td>24</td>
<td>6000 × 4000</td>
<td>255</td>
</tr>
</tbody>
</table>

4.2.3 Laser attenuation

The sampled laser beam must be heavily attenuated before it reaches the camera to prevent damage to the sensor’s electronics. Flexibility is also needed to adjust the
strength of attenuation depending on the energy density and power of the sampled beam.

Beam attenuation is achieved with neutral density filters, which both absorb and reflect part of the incident light. For well-spread laser light sheets and moderate/low power laser beams, standard photographic neutral density filters manufactured for consumer cameras are used, since they are inexpensive and readily available. They come on threaded mounts and are also sold in many different filter strengths, so that they can be stacked together in numerous combinations. A selection of 52 mm diameter filters were acquired with various strengths, outlined in table 4.2, to enable flexibility with different laser powers. A filter combination would ideally result in high pixel intensity values, just short of sensor saturation, in order to maximise the dynamic range of the sensor. A threaded stack of these filters (3 in figure 4.3a) is mounted directly to the camera body, (5), via a filter mount adapter, (4), slightly tilted from the sensor plane to prevent reflections returning down the beam path to the laser unit.

### Table 4.2: Neutral density filter strengths

<table>
<thead>
<tr>
<th>Optical Density</th>
<th>NDnumber Notation</th>
<th>% Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>ND2</td>
<td>50%</td>
</tr>
<tr>
<td>0.6</td>
<td>ND4</td>
<td>25%</td>
</tr>
<tr>
<td>0.9</td>
<td>ND8</td>
<td>12.5%</td>
</tr>
<tr>
<td>1.2</td>
<td>ND16</td>
<td>6.25%</td>
</tr>
<tr>
<td>1.5</td>
<td>ND32</td>
<td>3.125%</td>
</tr>
<tr>
<td>1.8</td>
<td>ND64</td>
<td>1.563%</td>
</tr>
<tr>
<td>2.6</td>
<td>ND400</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

Profiling high power laser beams however requires the addition of a laser-grade neutral density filter to reduce the initial intensity of the incident light. This prevents deterioration of the photographic neutral density filters, since their damage threshold and robustness to high power lasers is unknown. In these scenarios, a 2” diameter laser-grade mounted, absorptive neutral density filter (Thorlabs part number NE2R20A) is mounted to the front of the filter stack (1 in figure 4.3a). This filter has an optical density of 2.0 and a damage threshold between 5 J/cm² and 10 J/cm² for a 532 nm laser, with 10 ns pulses at 10 Hz (Thorlabs, Inc., 2016a). A threaded adapter (Thorlabs part number SM2A53) permits the connection between the laser-grade filter’s SM2 thread (2.035”-40.0, UNS-2 thread) and the photographic filters’ M52 × 0.75 thread (2 in figure 4.3a).

The filter stack is connected to the profiling camera body using a filter mount adapter, which combines a male camera lens mount on one end with a 52 mm female filter
(A) Laser profiling camera setup with sampled beam path (top view). Annotations denote 1 the laser-grade neutral density filter, 2 laser-grade filter threaded adapter, 3 photographic neutral density filters, 4 3D printed camera lens mount with epoxied metal filter thread, 5 interchangeable lens camera body

(b) Laser profiling camera setup (perspective view)

Figure 4.3: Laser profiling camera configuration using a Canon EOS-M camera body

(A) 3D render of filter adapter mount (camera side)  (B) Assembled filter adapter mount (filter side)

Figure 4.4: Neutral density filter adapter mount for a Canon EOS-M camera body
thread mount on the other. The bulk of this adapter is 3D printed (including the camera lens mount) and a metal 37 mm to 52 mm step up ring is epoxied onto the adapter to provide the filter mounting threads, as shown in figure 4.4b. The 3D printed model design depends on the required lens mount type, the Canon EOS-M in table 4.1 uses an EF-M mount while the Nikon D5200 and D5600 cameras use a Nikon F mount. The 3D printed component of the adapter was based on files1 from the 3D model repository Thingiverse, which were modified to incorporate a wedge-like shape in order to mount the filters at an angle relative to the camera’s imaging plane. This angle ensures that any laser reflections off the filters do not return back down the beam path and into the laser unit, which may otherwise overload and damage components.

4.2.4 Capturing and processing data

Laser profiles are captured as still images, recorded in uncompressed RAW files. The camera shutter is triggered externally using a wired remote2, that can be initiated either by a direct connection to a laser timing box or the manual press of a button. Camera bodies with integrated Wi-Fi/Bluetooth, or the addition of a Wi-Fi-enabled SD card, can enable the remote verification of laser alignment and previews of laser profiles without physically disturbing the camera setup during measurements. Access to uncompressed RAW files however often requires either USB tethering or physical access to the SD card. Tethered image capture, compatible with the Nikon cameras tested, allows the camera to be computer connected via USB while capturing images to streamline the rapid processing of recorded laser profiles. The free software package, digiCamControl, is used during tethered image capture to remotely access advanced camera control features and settings.

A lens cap with white cross-hairs through the centre (shown in figure 4.5) was made to aid alignment of the camera with the sampled laser beam. Since consumer photographic cameras use mechanical rather than global electronic shutters, the sampled laser beam is run at 1 Hz and images are captured with an exposure time of 1 second (at ISO 100) to ensure the entirety of a pulse is recorded. When manually

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1The adapter model for the Canon EF-M mount was based upon the “Canon EF-M Lens Mount Module” designed by PPK (found at http://www.thingiverse.com/thing:703383), and the Nikon F mount adapter was modified from the “Nikon F-Mount Pinhole Lens” model designed by kovo (found at http://www.thingiverse.com/thing:20993)

2Unfortunately, the Canon EOS-M camera does not feature a port for a wired remote as standard, so a free software add-on (Tragic Lantern version: tragiclantern-v31337.TRAGIC.2014Dec19.EOSM202) was loaded onto the camera to enable audio triggering of the shutter. The wired remote was implemented by plugging the remote wire into the camera’s 3.5 mm external microphone port. Short circuiting this connection causes an “audio” signal to be detected by the camera, which triggers the shutter. Both the Nikon D5200 and D5600 offer standard wired trigger connectivity.
triggered, the exposure is started in-between laser pulses, so that only a single pulse is captured in each image.

The captured images are recorded in colour (using a Bayer filter array), which can be viewed as $m \times n \times 3$ arrays to fully describe the red, green and blue colour data. Since lasers are inherently monochromatic, the interpolated colour channel closest to the laser wavelength can be isolated for any detailed analysis of profile cross sectional brightness. The remaining channels can show some signal leakage from higher intensity incident laser light, as well as capture any non-coherent light emitted from the laser, and this can otherwise distort combined RGB brightness intensity distributions. Bayer filter interpolation effects are considered to have a negligible impact on results, since camera sensor pixel sizes (approx. 0.004 mm) are much smaller than the features of significance in a laser profile (which are typically on the order of 0.1 to 1 mm). Images must also be vertically flipped in post-processing, to compensate for the absence of any lens fitted to the camera (which would otherwise vertically flip the image through the optics).

4.2.5 Results

Figure 4.6a and 4.6b show sample unprocessed laser light sheet and beam profiles respectively, using the laser profiling camera. Note that the concentric ringing visible in the figure 4.6b beam profile is considered typical for this laser unit, due to thermal lensing effects from the laser rods. These images demonstrate the sensitivity of the profiling camera compared with typical burn test techniques, where some burn papers
Figure 4.6: Unprocessed laser camera profiles of a Spectra-Physics PIV-400 laser system

may not even respond to highly spread light sheets. The resolution of these laser profiles enable detailed analysis of the light sheet and beam centroids to be performed.

4.3 Performance analysis

In order to be of use for laser beam alignment and troubleshooting, a laser beam profiler must demonstrate an ability to faithfully reproduce laser beam intensity distributions. The proposed laser profiling camera design, using Canon EOS-M, Nikon D5200 and Nikon D5600 camera bodies, is examined for its performance studying laser beams.
4.3.1 Camera sensor response

The wavelength response of a camera sensor can radically change with different sensor architectures and even subtly vary from one model and manufacturer to another. Understanding how these behaviours interact can provide some context for detailed investigations of captured laser profiles. Typical red, green and blue spectral responses from Canon and Nikon cameras are shown in figure 4.7. These results were captured by illuminating each camera sensor with monochromatic light using a wavelength tuneable monochromator, and recording the sensitivity of each red, green and blue pixel colour group. The unprocessed 12-bit pixel count per unit time data are plotted for different exposure times over a range of visible light wavelengths, measured in ångströms ($10^{-10}$). While the cameras in the plot are distinct from the models used in this study for laser profiling, the responses illustrate variations that can occur in Bayer filter leakage from one colour channel to another. Figure 4.7 shows that the Canon 40D sensor exhibits slightly lower sensitivity than the Nikon D300, along with greater leakage into the red channel at green light wavelengths.

4.3.2 Brightness linearity correction

Studying the characteristics of a laser beam profile relies on predictable and intuitive behaviour of the profiling medium. When profiles are studied in detail and quantified,
such as plotting cross-sectional slices of an imaged beam profile, a linear relationship between incident light and recorded pixel intensity is desirable for straightforward analysis. However non-linear brightness relationships are frequently applied to digital images using a parameter known as gamma correction, a power law adjustment of the input luminance/output brightness relationship. Gamma correction aims to better match images to the human eye’s non-linear perception of brightness, or to compensate for non-linear responses found in display devices such as computer monitors. A gamma correction of 1 yields a linear input/output relationship, while a non-linear gamma of 2.2 is commonly used for most graphics viewed and processed on computers. While images processed with gamma correction $\gamma \neq 1$ may be interpreted as more visually accurate and representative (see the comparison in figure 4.8), numerical comparison of pixel intensities reveal distortions in brightness distributions due to the non-linear input/output relationship. Linear correction of the brightness (applying a unity gamma correction) must consequently be applied to any laser profiles prior to numerical analysis.

RAW image files are needed to perform linear brightness correction, since they contain minimally processed image data, including linear pixel intensities. Compressed and processed image files, such as JPEG formats, often contain an explicit gamma correction factor that cannot be easily modified. In contrast, RAW image files allow batch conversion with a user-defined gamma correction to a processed image file, before subsequent analysis. DCRaw is a script-based, open-source RAW image conversion tool developed by Dave Coffin (2015) that enables RAW processing to 16-bit TIFF images with linear brightness output. The ability to export 16-bit images also allows the full bit depth of the RAW image to be exploited in analysis, as compared with 8-bit data found in JPEG images.

Visually, an image processed with linear brightness (a gamma correction of 1) appears...
very dark when compared with traditional image processing (see figure 4.8). However, numerical comparisons confirm the impact of linear brightness processing. To verify this, multiple images of a static scene with different shutter speeds can be captured. For the purposes of this comparison, all images were processed with both linear and nonlinear processing in DCRaw as 16-bit TIFF images, with a fixed white level and no white balance applied (as a result they do not necessarily appear physically accurate representations of the scene). If the average image intensity across each frame is calculated, it is expected that doubling the exposure time would also double the average image intensity. Yet this is not necessarily the case. As plotted for the Nikon D5200 in figure 4.9, this expected behaviour only occurs with linear brightness correction, which applies a gamma correction of 1.

Use of RAW image files and linear brightness correction is therefore crucial to any quantitative analysis of laser profile distributions. Unless stated otherwise, all images of laser profiles in this study will be presented using nonlinear processing so as to be visually representative of the beam, while all plotted cross sections and numerical pixel intensity comparisons will use linearly processed profile image data.

### 4.3.3 Camera profile validation

After verification of the camera profiler’s more fundamental behaviours and performance, camera profile results must ultimately be compared with existing, accepted methods for laser profiling. As discussed in section 4.1.1, burn tests are a common
and widely adopted method for inexpensive and rapid laser profile verification. These techniques consequently provide a robust means of validating the laser profiles captured with the camera system. Note that the images of all burn tests (using both Fuji FP-3000B and Zap-It papers) shown here have been enhanced for contrast and tonal levels to maximise clarity and emphasise the shape of the laser profile.

A comparison of single-shot laser profiles of head 1 from a 400 mJ/pulse Spectra-Physics Quanta-Ray PIV-400 laser is shown in figure 4.10, measured 67.5 cm from the laser unit. Figure 4.10a uses the purpose-made Zap-It laser burn paper, where the grid has a 2 mm spacing. This technique yields very little dynamic range and definition over a single shot, showing only a basic silhouette of the laser beam. Figure 4.10b uses unexposed and developed Fuji FP-3000B peel-apart instant pack film and displays far superior dynamic range and definition of the beam. The Fuji film profile in particular is highly representative of what is seen with a laser camera profile of the laser beam, shown in figure 4.10c. Given that each profile captures a different individual pulse of the beam, which can introduce jitter and other shot-to-shot variations in the profile, the camera image displays excellent consistency with results from the other profiling methods.
Head 2 from the same laser is compared in figure 4.11 at an identical 67.5 cm measurement distance. Once again the camera profile shows additional detail and very similar behaviour to the other tests, in particular closely matching the intensity distribution found using the Fuji film method.

Other laser units can be compared to further reinforce camera profiler performance. Figure 4.12 compares a Zap-It burn profile and laser camera profile of head 1 from a 200 mJ/pulse Quantel Evergreen 200 laser at a 1.2 m distance from the unit. The same diamond or teardrop beam shape is visible using both profiling techniques. Close agreement also exists between the Zap-It and laser camera profile for head 2 of the same laser at 1.2 m in figure 4.13. Note that an earlier iteration of the laser profiling camera was used to capture the profiles shown in figures 4.12b and 4.13b, resulting in minor secondary reflections visible at the bottom of the laser profiles. However, these secondary reflections are no longer observed when using the final profiling camera design outlined in this chapter.

Further comparisons can be made by directly overlaying Zap-It burn test outlines on camera profiles. This is achieved by applying image processing techniques to an image of the burn profile, to extract the burn outline. The original image of a Zap-It burn paper profile (1 in figure 4.14) is converted to greyscale and contrast
Figure 4.14: Image processing sequence for burn test images

stretching is applied until a binary image is produced. Grid lines within the laser contour are manually removed using image-editing software. The resulting two-tone image is processed in MATLAB with a Canny-method edge detection algorithm. A continuous outline of the burn profile is calculated by dilating detected edge boundaries and filling in small holes. A boundary is traced around the resulting region, defining the burn test outline. The outline is rescaled to match the scaling of the camera profiles, with the aid of the 2 mm spaced grid on the burn paper to calculate the scale factor. The outline is then overlaid on the camera profile by matching the unweighted, geometric centroid of the outline with that of a thresholded camera profile. For a given camera filter combination, this method can also illustrate the approximate sensitivity of burn test methods.

A comparison of the 400 mJ/pulse Spectra-Physics Quanta-Ray PIV-400 laser burn tests and camera profiles are shown in figure 4.15. Note that these laser burn tests and camera profiles document separate laser pulses, where subtle shot-to-shot variations in a laser’s profile can occur. Given this, the size and shape of the burn test outlines are very consistent with camera profile results, approximately tracing similar contours around both laser head camera profiles (which employ common colour axis limits).
Chapter 4. Laser profiling camera

A similar comparison can also be made to the 200 mJ/pulse Quantel Evergreen 200 laser profiles, shown in figure 4.16. Excellent agreement is also shown between the burn test outlines and camera profiles, all of which were captured at the same 1.2 m distance from the laser unit.

Finally, a comparison between the results from the proposed laser profiling camera design and a DataRay WinCamD-LCM commercial beam profiling camera capturing an InnoLas Spotlight Compact PIV 400 beam is shown in figure 4.17. Given that these profiles capture separate pulses of the laser, very good agreement can be observed in the characteristics and detail of the beam profiles. These results all validate the
Figure 4.17: Comparison of a commercial WinCamD-LCM profiling camera and the outlined profiling camera design, profiling an InnoLas Spotlight Compact PIV 400 laser beam.

suitability and accuracy of the proposed laser profiling camera design for the detailed study of laser profiles.
Chapter 5

Diagnostic applications of a laser profiling camera

Laser profiling devices capable of examining a laser’s intensity distribution in detail, such as the profiling camera design discussed in Chapter 4, can be routinely used to investigate and optimise laser performance for an experiment. By monitoring the behaviour and characteristics of a laser system, experimental setups can be configured to best maximise their use of the laser beam. This discussion considers investigations of the undeformed laser beam, as well as analysis of the laser light sheet over a PIV field of view. Some applications for profiling cameras with other laser-based flow measurement techniques are also presented.

5.1 Profiling the laser beam

Examining the laser beam as it leaves the laser unit offers the most fundamental insight into a laser system’s behaviour. The root cause of many correlation quality issues arising in PIV measurements can be traced to undesirable characteristics found in a laser beam’s intensity distribution.

5.1.1 Laser beam profile characteristics

Many variables contribute to the beam profile that is produced by a laser system. System architecture, laser trigger and delay timing, the tuning of system settings, hardware age and condition, ambient conditions, and whether the laser has been appropriately warmed-up all influence the behaviour of the laser’s beam profile.
Therefore differences in beam profile can often occur between the two cavities of the same PIV laser system, as well as between identical laser models.

Figure 5.1 shows the diversity of beam profiles observed from each cavity of two identical Spectra-Physics Quanta-Ray PIV-400 lasers. The beam profile of higher power lasers, such as these 400 mJ/pulse 532 nm Nd:YAG systems, can feature concentric ringing patterns due to thermal lensing effects from the laser rods.

The symmetry and uniformity of a laser’s beam profile can have an important impact on PIV measurements, since these imperfections can persist as the beam is spread into a light sheet. Irregular or biased intensity distributions of the light sheet can result, which can have unexpected and unwanted effects on the thickness of the measured field of view. If the intensity distribution of the two laser cavities are not similar (as can be observed in some of the examples in figures 5.1), there will be an increase in the out-of-plane loss-of-pairs, causing a drop in the correlation quality of the measurement. Consequently, laser cavities must be tuned to achieve good matching of their intensity distributions, and it is often easier to match two symmetric and uniform laser profiles, than to match two distinct and irregular laser beams. This laser mismatch and overlap effect will be discussed in greater detail in Chapter 7.
Knowledge of a laser’s beam profile can also instruct the configuration of beam spreading optics in a PIV experiment, which form the light sheet. If a laser beam displays a clear asymmetry across a particular axis, it may be wise to consider spreading the light sheet along that same axis. This will avoid the non-uniform laser intensity appearing over the thickness cross-section of the light sheet, where it could otherwise hinder the overlap and matching of the two light sheet profiles.

5.1.2 Beam profiles throughout a PIV setup

A profile of the laser beam can not only aid the selection of the optimal axis to spread the light sheet, it can also provide feedback on the configuration and placement of light sheet optics and other components along the beam path. For example, some experiments use a slit or iris to clip part of the laser beam. Profiling the laser before and after these components can enable their placement and adjustment to be refined, isolating the preferred region of the laser beam. Figure 5.2 illustrates the impact an iris’ setting can have on a laser beam and the intensity distribution of the beam profile. The iris was located approximately 2.7 m from the laser body, while the profiling camera was placed a further 2.5 m from the iris.
5.1.3 Laser head alignment

A laser profiling camera offers a precise, systematic approach to tuning the alignment of the two laser beams used in PIV. Profiles of both laser beams are captured, without disturbing the profiling camera, so that the relative positioning of each cavity can be measured. The centroid location of the laser beam profiles, weighted by the intensity distribution of the beam, can then be compared. Some small shot-to-shot variations in the intensity distribution and beam location can occur between laser pulses (as seen by the scatter in the figure 5.3 example), so a series of beam profiles from each head must be captured and their locations averaged. All of these measurements should only be performed once the laser system has been warmed-up appropriately – the consequences of neglecting this warm-up period will be the subject of Chapter 6.

5.1.4 Identifying laser faults

Detailed profiling of laser beams also enables monitoring of laser performance and early identification of system faults impacting the laser beam profile. Observed changes to laser beam characteristics can therefore be used to inform the service schedules of laser equipment.

For example, laser profiles of a Quantel Evergreen 200 system revealed degradation in laser beam quality from figure 5.4a to figure 5.4b over time. However after servicing, the laser beam profile had been corrected to the profile shown in figure 5.4c. Note that
variations in the apparent intensity between laser profiles are caused by differences in the neutral density filter combinations used to capture the laser profiles.

More subtle laser system faults that would be difficult to observe using laser burn tests can also be identified with a beam profiling camera. Figure 5.5 shows the sequential degradation of a laser’s beam profile over time, later found to be caused by burn marks forming on the laser cavity’s Pockels cell. These marks created silhouettes in the laser beam profile, which produced a complex series of diffraction patterns that disturbed the intensity distribution of the beam. These patterns were not clearly
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5.2 Profiling the light sheet

Profiling a light sheet’s intensity distribution over a PIV field of view offers the most practical application of a laser profiling camera for PIV experiments. These measurements reveal the cumulative impact of the laser and optics configuration on the quality of PIV data. The profiling camera captures images of the light sheet (figure 5.6a), which are then corrected for linear brightness, and a slice is taken through the light sheet cross-section to obtain the intensity profile (figure 5.6b).

The direct impact of changes to the experiment’s optical configuration can be observed on the light sheet profile over the PIV field of view in this way. Figure 5.7, for example, shows the influence that additional clipping from an adjustable metal plate midway along the beam path has on the light sheet intensity profile over the measurement field of view.

5.2.1 Light sheet alignment

Detailed and repeatable light sheet profiling can inform adjustments to the alignment and overlap of laser cavities, after the coarse beam adjustments discussed in section 5.1.3 are performed. While highly dependent on a laser’s beam profile, the quality of light sheet overlap can also vary across the spread of a light sheet. Figure 5.8
Chapter 5. Diagnostic applications of a laser profiling camera

Figure 5.7: Effect of light sheet clipping measured by a laser profiling camera.

Figure 5.8: Variation in sheet overlap and intensity across a light sheet’s spread. A schematic of the laser profile sampling arrangement across the spread of the light sheet is shown above.
Chapter 5. Diagnostic applications of a laser profiling camera

5.3 Diagnostics with other laser equipment

Laser profiling cameras can be equally useful with other laser-based measurement techniques. For example, diagnostic testing of a Laser Doppler Anemometer (LDA) was performed using the laser profiling camera design outlined in Chapter 4. This Dantec FlowExplorer laser system consists of $\sim 90$ mW 660 nm red and 785 nm infrared diode laser beams, and flow experiments had indicated excessive noise measured from the 660 nm red beam channel. Diagnostic measurements of the system revealed two important, but subtle inconsistencies in laser behaviour. Figure 5.9 shows unbalanced intensity of the two 660 nm red beams, in contrast with the similar intensities of the 785 nm beam pair. Multiple beam profiles of the 785 nm laser beams also indicated
significant time-varying distortions in the intensity profiles of the beams compared with the 660 nm laser. This change can be observed in the successive images shown across the top row in figure 5.10, relative to the invariance of the 660 nm red beam image sequence in the bottom row. These measurements assisted with the troubleshooting of this equipment and were provided to the manufacturer to aid the service of the hardware.
Chapter 6

Laser transient and warm-up effects

This chapter incorporates the publication [K Grayson, CM de Silva, N Hutchins and I Marusic. Beam stability and warm-up effects of Nd:YAG lasers used in particle image velocimetry. Measurement Science and Technology, 28(6), 2017].

Laser beam drift and stability performance, discussed in section 5.1.3, are commonly considered when acquiring a new laser system. These characteristics are specified by manufacturers for a laser operating at equilibrium conditions, after sustained system operation. However, prior to reaching this state of equilibrium, a system’s laser beam can exhibit greater variations in drift and stability. The duration of these warm-up transients and their impact on laser behaviour is often underappreciated. Laser-based flow visualisation techniques, such as particle image velocimetry (PIV), are particularly sensitive to these changes in the performance of the laser system (see Chapter 7). In practice, the magnitude of these warm-up behaviours is sufficient to interfere not only with experimental measurements, but also frustrate beam and optical alignment during the setup of an experiment. While laser warm-up effects are known anecdotally or through experience, these behaviours have not been formally documented or quantified. The study in this chapter investigates and quantifies typical transient and shot-to-shot behaviours of pulsed Nd:YAG lasers used in PIV measurements, to determine a set of recommendations for PIV best-practice which can minimise these dynamic laser effects.

Manufacturers quantify the long and short term stability of a laser using the beam drift and pointing stability parameters respectively. These characteristics can vary significantly between various laser types, due to differences in laser architecture
and operation. While there are few studies which investigate laser beam stability performance in practice, even fewer studies to date examine the specific behaviour of pulsed Nd:YAG lasers relevant to PIV experimentalists.

Nd:YAG lasers are known to have greater beam pointing variability than the continuous lasers used in early PIV experiments (Raffel et al., 1996). Yet the additional power and functionality of pulsed lasers are now necessary for most high performance PIV applications. The beam pointing stability of a Nd:YAG is documented by Fix and Stöckl (2013) when investigating the coupled stability relationship between an Optical Parametric Oscillator (OPO) and its Nd:YAG pump laser. Siders et al. (1994) also briefly discuss the beam pointing scatter of a high repetition rate Nd:YAG, used to pump a Ti:Al₂O₃ laser. Furthermore, studies have documented the beam pointing stability of other laser variants, including Copper Vapour (Dixit et al., 2008), Titanium:Sapphire (Groß et al., 2011) and Ho:YAG pumped OPO (Schellhorn et al., 2007) laser systems. These studies all focus on the beam pointing characteristics of a warm laser operating under steady state conditions, however transient effects are also of interest for some laser applications. Gray et al. (2001) documents the warm-up drift of two small He-Ne lasers, illustrating the reduction of laser drift during the warm-up process. Yet the specific nature and duration of Nd:YAG warm-up transients for PIV lasers are not often known by laser users, nor documented by manufacturers. When performing PIV measurements, this can either result in capturing data during the laser warm-up period when the laser alignment is less stable, or waiting unnecessarily long time periods to ensure an equilibrium state is reached, while depleting the life of many laser components. Furthermore, laser drift during warm-up can also affect the accuracy of laser alignment with experimental optics and laser beam overlap while setting up PIV experiments, where laser warm-up procedures may not be quite as studiously observed. In such a scenario, the laser beam may shift from its intended, aligned location after appropriate warming of the system.

Comparisons between various laser units and system warm-up sequences are discussed in this study to determine optimal laser start-up procedures for PIV best practice, which can minimise the effects of laser transients. Determining the working shot-to-shot beam pointing stability and independence of each laser head once in an equilibrium state also establishes the best beam overlap behaviour that can be expected in PIV experiments.
6.1 Characterising laser warm-up transients

The warm-up transients of a laser system can be determined by studying the movement of the laser beam and changes to the beam’s intensity distribution over time. A laser profiling camera offers a robust and repeatable means of measuring the single-shot position and energy distribution of the laser beam. In this study, the modular and flexible profiling system described in Chapter 4 is used, consisting of a consumer digital camera and off-the-shelf components. Further details regarding this camera system can be found in Chapter 4 and in Grayson et al. (2018).

Three different laser systems are considered and compared in this study. Lasers A and B are large, identical dual-cavity Spectra-Physics Quanta-Ray PIV 400 lasers, whereas Laser C is a smaller, portable dual-cavity Quantel Evergreen 200 PIV laser system (see Table 6.1 for additional laser specifications). Collectively these laser units cover a range of typical PIV lasers used in laboratory experiments. While we note that the results and conclusions from this investigation should apply to many PIV laser systems, the particular performance characteristics of the lasers in this study may not be representative of all lasers of this type, and may be specific to these laboratory systems. The laser flashlamps of each laser system are set to their nominal repetition rates for all measurements, while the Q-switch (commonly a Pockels cell) frequency is limited to 1 Hz for these measurements. However, note that since the capture rate of the laser profiling camera used in this study is limited to approximately 0.2 Hz, laser profiles are measured on every 5th pulse. The warm-up behaviour of each laser cavity is profiled in isolation. Horizontal and vertical components of laser position are calculated from the centroid of each laser beam profile, weighted by the laser beam intensity distribution.

In order to assess the worst-case laser warm-up scenario, the laser and cooling systems are switched on and fired from cold. Figure 6.1 compares the vertical displacement ($\delta_y$) of Laser A’s head 1 and 2 weighted centroids during warm-up, as measured on

<table>
<thead>
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<th>Parameter</th>
<th>Laser A</th>
<th>Laser B</th>
<th>Laser C</th>
</tr>
</thead>
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<td>Spectra-Physics</td>
<td>Quantel</td>
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</tr>
<tr>
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<td>400 mJ/pulse</td>
<td>200 mJ/pulse</td>
</tr>
<tr>
<td>Beam Diameter</td>
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<td>~9 mm</td>
<td>~6 mm</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>15 Hz</td>
</tr>
</tbody>
</table>
the laser profiling camera’s sensor at 0.67 m from the laser unit. The thin, pale lines indicate the shot-to-shot variation in the laser beam location, or the beam pointing stability. A moving average filter is applied to these data to produce the thicker lines, which illustrate the overall laser beam drift, or the longer term trend in the movement. This plot illustrates that while the two laser heads within Laser A may be reasonably well aligned (within 0.1 mm) once in an equilibrium state, this consistency may not necessarily apply to the dynamic behaviour of the heads during warm-up. Figure 6.1 shows noticeably different warm-up drift between the two laser heads, head 1 drifts approximately 0.4 mm while head 2 drifts more than twice as far (almost 1 mm). Despite this, the warm-up transients from both laser heads do begin to stabilise after similar durations of about 15 minutes. Consequently any PIV measurements, changes to experimental optic alignments, or tuning of a PIV laser’s head 1 and 2 overlap may provide false results if performed prior to the laser reaching a state of equilibrium (< 15 minutes from cold in this case). PIV experimentalists should be particularly aware of the impact this drift can have when aligning experimental optics outside the laser or tuning the overlap between the two beams. Some modern PIV lasers, including Laser C in this study, do not offer the flexibility for users to adjust the laser overlap. However, figure 6.1 demonstrates that the quality of beam overlap can change dynamically throughout the warm-up period. A “quick alignment check” of either the laser beam overlap or the beam path through experimental optics is of extremely limited value unless the laser has been warmed up appropriately.

A more detailed analysis of transient laser warm-up effects can be studied if the curves
Figure 6.2: Angular laser beam movement of each laser cavity in Laser B (top two rows) and Laser C (bottom two rows). The horizontal and vertical drift is shown in left and right columns (and by solid blue and dashed red lines) respectively. The faint coloured lines show the shot-to-shot movement, while the brighter, thick lines show the filtered trend depicting laser drift are plotted from the origin. This emphasises the magnitude of laser transients from laser startup until the time required to reach stability. Laser drift is also considered to be dominated by angular rather than translational variations, so angular drift ($\alpha_x$ and $\alpha_y$, using a right-handed coordinate system with an origin at the laser unit’s beam aperture) is used to generalise the motion of the laser beam. The measured horizontal and vertical drift of Lasers B and C are compared using this metric in figure 6.2. A representative physical shift over a 4 m beam path ($\delta_x$ and $\delta_y$) is also included on the right-hand ordinate for reference. The vertical drift ($\alpha_y$) of both lasers generally exhibit significantly more variable transient behaviour than the horizontal drift ($\alpha_x$), reaching up to the equivalent of 1 mm drift over a 4 m beam path. Furthermore, the vertical transients from Laser B are slightly larger than the corresponding drift shown by Laser C. It is hypothesised that drift is largely
determined by the increasing temperature within the system, causing the thermal expansion of laser components and the laser head chassis. We postulate that since components are commonly mounted vertically onto a baseplate, thermal expansion would predominantly affect the vertical drift of the laser beam. These trends and general behaviour were consistently observed in each laser during multiple warm-up transient measurements. However, subtle variations in the magnitude of the laser drift can be found with measurements from the same laser system under different ambient conditions. Given the intimate link between transients and the temperature of the laser system (discussed further in section 6.2), ambient temperature can, in particular, influence the extent of transient drift.

Differences in the warm-up drift behaviour of Laser B and Laser C, and even head 1 and 2 from the same laser system, can be clearly observed in figure 6.2 despite generally similar trends. These distinctions in warm-up characteristics can be attributed to the diversity in the design and architecture of laser systems. The cooling system design and efficiency (water/air or water/water configurations, for example), the materials used in the laser head (and particularly their thermal characteristics), configuration of the cavities within the laser head, optics, and condition of the hardware can all influence the precise manifestation of laser warm-up effects. Laser B is a physically larger and higher power laser system than Laser C, requiring greater electrical energy input which can produce steeper thermal gradients, and possessing a larger chassis structure with a higher thermal mass. Additionally while Laser B is capable of instant operation on start-up, Laser C has an automated initialisation procedure which delays the operation of the laser and may decrease the apparent impact of laser transients. The comparatively large horizontal drift observed with Laser C’s head 2 might also suggest that there is a difference in the mounting configuration of this head compared with head 1. Since Laser C is a compact laser system, such differences in the internal mounting of laser cavities and associated optics are more likely due to strict space constraints. Yet despite these differences, both lasers are largely stable after 10 to 15 minutes.

So even with different Nd:YAG pulsed laser systems, similar transient characteristics exist during the warm-up of each laser which are significant enough to affect PIV measurements. However, we note that thoroughly assessing the detailed characteristics of a specific laser system requires individual warm-up drift measurements of that system, due to the diversity of laser architectures. The percentage misalignment of a laser beam can be defined by $\frac{\delta_{\text{max}}}{d} \times 100$, where $\delta_{\text{max}}$ and $d$ describe the maximum drift and beam diameter in millimetres. This percentage remains constant with any optical scaling of the laser beam, therefore a laser sheet will experience the same percentage misalignment relative to its thickness as observed with the same laser’s
beam when compared with the beam diameter. Figure 6.2 shows a drift of up to 1 mm over a 4 m beam path and given that Laser B has a beam diameter of 9 mm, the misalignment of this laser can be expressed as up to 11.1% of the beam diameter during warm-up. While other operating conditions and laser units (even if they are the same model system) may alter this percentage, the magnitude of this movement nevertheless remains a significant fraction of the beam diameter. Therefore, the rationale for an appropriate laser warm-up procedure prior to performing any laser alignment, overlap adjustment or PIV image capture is clear. But a greater understanding of the processes within the laser warm-up cycle that generate these transients can aid and inform the development of an optimal warm-up sequence.

### 6.2 Impact of laser subsystems on warm-up transients

Systematic measurements of different laser warm-up sequences can help to determine the relative impact of laser subsystems on transient behaviours. Only one laser cavity (head 2 from Laser A) is used for this comparison, since these general behaviours are expected to be consistent among various pulsed Nd:YAG laser cavities. Three test scenarios are considered, and their transients compared. Case 1 involves operating the laser directly after turning on the cooling and flashlamps, identical to the tests performed in section 6.1. Case 2 consists of running the cooling system and laser power supply for 90 minutes prior to operating the laser, while Case 3 is performed...
after running the laser flashlamps (along with the power supply and cooling systems) for 60 minutes prior to operating the laser. We note that Case 1 and 2 scenarios do not necessarily reflect long term best practice laser operating procedures, these tests were only performed to isolate the laser subsystem effects on warm-up transients. The test cases are summarised in table 6.2 and the horizontal and vertical laser warm-up drift associated with these three scenarios is shown in figure 6.3. Cases 1 and 2 display very similar vertical stability behaviour ($\alpha_y$), depicting a large warm-up transient for the first 10 to 15 minutes of operation, consistent with the results discussed in section 6.1. Some horizontal drift variability is also observed during warm-up for Case 1, although the magnitude of this variation is comparatively small and the majority of the transient is relatively short-lived. The horizontal drift of Case 2 appears to be steady, despite the large vertical transient which is observed. Case 3 however shows very limited long term drift in both the horizontal ($\alpha_x$) and vertical ($\alpha_y$) directions. These comparisons therefore suggest that the key contributor to laser warm-up transients (impacting the vertical drift) is associated with the operation of the laser flashlamps, rather than simply the cooling system or the temperature stabilisation of the harmonic generator. Furthermore, minor horizontal drift transients appear to be linked with the operation of the laser cooling and power systems, although this result is not as conclusive and has a relatively small impact on the total transient behaviour of the system. It is also worthwhile noting that a comparison between the Case 1 behaviour of Laser A in figure 6.3 and Laser B in figure 6.2 reveal large differences in the drift magnitude, despite similar qualitative trends. This illustrates the degree of fluctuations in transients that can exist, even between identical laser models, due to variables such as the conditions of the laser hardware.

To further understand how flashlamp operation influences laser transient characteristics, the temperature changes within the laser system were examined. A thermal camera (a second generation Flir One camera) was used to capture the key sources of heat during laser warm-up and operation. Figure 6.4a shows a visible-light view of the laser system’s internal configuration. The two laser cavities 1 are shown, with two flashlamp assemblies within each cavity. The laser’s harmonic crystal 3
and the harmonic crystal thermal regulator system (2) are highlighted in the bottom of the image. Figure 6.4b shows the cold laser internals, consistent with the Case 1 test scenario. While the majority of the laser is cold, some heat can be seen from the harmonic crystal and its associated thermal regulator system, which maintains an electrical power connection while the laser is off. Figure 6.4c shows the Case 2 scenario, where the cooling system and laser are on, and the wires leading to each flashlamp assembly are now warm. Figure 6.4d was captured after the right-hand laser cavity flashlamps were run for 15 minutes. In this image, the right flashlamps and associated connections have heated considerably relative to the rest of the laser system, while the left flashlamps have moderate warming due to the heating of the common water cooling circuit. Most of the laser system therefore experiences slow, but steady heating during operation, while the flashlamp housings exhibit much more rapid heating on start-up. Given the significant electrical energy input required to drive the flashlamps, local heat dissipation observed around the flashlamps is to be expected.
This localised flashlamp heating is examined in detail in figure 6.5. Figure 6.5a shows the visible-light image of the laser flashlamps, taken from the opposite end of the laser compared with the views in figure 6.4. The flashlamps associated with one laser cavity extends along the left of the image, while the other laser cavity runs along the image-right. Figure 6.5b shows the Case 2 scenario, where heat can be observed from the wires running into each flashlamp assembly, 1, as well as from a vent, 2, in the right of the image leading to the electrical circuitry beneath the laser baseplate. Figure 6.5c is captured after the left-hand laser cavity flashlamps have been run for 15 minutes. Moderate heating of all flashlamp assemblies and cooling system tubing can be observed as the system cooling water warms. However the left-hand flashlamp assemblies, cavity wires and wire terminals are warmer than those in the right-hand laser cavity.
While these thermal images offer an insight into the localised regions of heating during laser operation, higher resolution measurements documenting how these temperatures change during laser warm-up are required to understand how flashlamp operation influences laser transient characteristics. Thermocouples were placed on a cavity’s flashlamp assembly (B in figure 6.5c), a key source of localised heating, as well as the baseplate of the laser chassis (A in figure 6.5c). Examining the difference between these two temperature measurement locations (shown by the blue line in figure 6.6) reveals a temporary thermal imbalance transient during the initial operation of the laser. Furthermore, the duration and characteristics of this imbalance are similar to that of the observed vertical laser drift transient (shown by the red line). It is therefore likely that the initial uneven heating within the laser system is a key contributor to the observed laser beam vertical drift behaviour during warm-up. After approximately 10 minutes, the thermal changes throughout the laser unit reach an equilibrium state, suppressing further laser drift. The subsequent slower, persistent warming of the laser results in only minor beam drift, likely due to the uniformity of the temperature change throughout the laser unit.

In practice, these results imply that laser warm-up may only require operation of the flashlamps for a prolonged period prior to laser use in order to avoid the most severe beam stability transients. The Q-switch does not need to be run at any stage during this time, which also removes the inconvenience and implications of direct light output from the laser system. This behaviour is also of significance during PIV measurements.
where pauses in image capture can be required to clear camera buffers. During this period it may be tempting to switch off the laser fully, but complete shutdown of the system can reintroduce further transients on laser restart. To illustrate this behaviour, figure 6.7 compares the vertical transient of Laser B head 1 started from cold against a warm, stable laser (the same Laser B head 1) that has been shut down for only 60 seconds prior to restart. Due to the thermal factors influencing warm-up behaviour, the restart transient appears to be less severe and stabilise fractionally quicker than a laser run from cold. However as shown in figure 6.7, warm-up transients are present irrespective of the shutdown duration and still require approximately 10 minutes to settle. Simply halting the Q-switch trigger, while maintaining flashlamp operation, can avoid laser output and limit the re-emergence of transients during the next set of PIV measurements.

6.3 Dual cavity coupling of shot-to-shot beam movement

Thus far this study has explored the changes in stability of a single laser cavity during the warm-up phase of the system. PIV measurements typically employ dual-cavity lasers, which allow two independent laser pulses to be fired over any time interval. Two laser cavities also result in two separate laser transients arising from the system, one corresponding to each cavity or laser head. Here we seek to determine if the stability of the two laser cavities exhibit coupled or independent behaviour during the
warm-up phase as well as the steady state operation of a PIV laser. This will have consequences for the overlap of PIV laser light sheets, and by extension the quality of correlation results. Measurements to assess this relationship are acquired using a laser profiling camera, imaging both of the laser beams simultaneously. Laser B is used for these measurements, where the beams are deliberately misaligned horizontally such that two distinct laser profiles can be observed side-by-side on the same camera sensor. Both cavities are fired from cold to measure the full transient and steady state behaviour of the two laser beams. It should be noted that negligible differences between operating one, or both laser cavities simultaneously are observed in the laser beam drift characteristics and in the time required for the laser to reach a steady state.

Rather than plot the drift of both laser cavities independently, changes in the relative separation of the two laser beams (by subtracting the time-varying angular drift of laser cavity 2 from that of laser cavity 1) are of greatest significance in this investigation. Time-varying relative angular drift indicates different drift behaviour from the two laser cavities, while constant relative angular drift suggests that both laser beams are either stationary or drifting together. The relative motion between the laser cavities is emphasised by initialising the data with zero angular drift. These horizontal and vertical relative angular drift results are shown in figure 6.8. Variations in both the horizontal and vertical relative angular drift are observed over the first 10 to 15 minutes of laser operation, when the most significant beam pointing transients are also observed (discussed previously in sections 6.1 and 6.2). This result therefore
implies that the transient behaviour of the two laser cavities is relatively independent. Such an observation also reinforces the hypothesis presented in section 6.2, where key factors influencing the transient behaviour reside in each individual laser cavity, and more specifically relating to the operation and mounting configuration of the flashlamps. Beyond 15 minutes of operation however, the mean angular difference of the two laser heads remains relatively constant, consistent with the greater pointing stability observed after warm-up in earlier single cavity results.

The same vertical and horizontal relative angular drift data can also be presented as a scatter plot, where data points located at (0,0) indicate no change in the relative x and y locations of the two laser beams when compared with their initial separation. These results are shown in figure 6.9, where the colours indicate the laser runtime from cold. The greatest scatter in the relative laser beam location occurs just after laser start-up, in agreement with the findings presented in figure 6.8. Crucially, we observe tighter clustering of relative laser beam locations after prolonged laser operation. This behaviour indicates that correct laser warm-up procedures not only achieve lower drift of each individual laser beam, but also greater consistency in laser beam overlap due to relative stability of the two laser cavities in a PIV laser.

While the mean relative location of the laser beams reach an equilibrium state after more than 15 minutes of laser operation, a shot-to-shot relative beam pointing jitter remains (see figure 6.8). Statistically characterising this variation can establish a practical limit for an experiment’s light sheet overlap, which influences the quality of PIV image correlation. Relative angular laser profile drift after 30 to 60 minutes of
laser operation is isolated for further processing, from the dataset used earlier in this section. Correlating the shot-to-shot movement of the two laser beams reveals no clear coupling between the behaviour of the two laser heads once at thermal equilibrium. However, a histogram of this jitter (not reproduced here) suggests a similar statistical spread of beam pointing behaviour from both laser cavities. The standard deviation of the relative angular drift ($\alpha_1 - \alpha_2$) in the horizontal and vertical directions from this dataset is found to be 14.7 µrad and 13.6 µrad respectively. Therefore even if perfect mean overlap of the laser beams can be obtained, and if the system has been warmed up sufficiently to avoid laser transients, this shot-to-shot beam pointing jitter can cause small overlap misalignments for PIV image pairs. To illustrate the impact of this jitter, we can assume a perfectly overlapped PIV configuration using the data from Laser B. The calculated magnitude of shot-to-shot variation over a 4 m beam path implies that 68% of laser pulse pairs will have a percentage misalignment of less than 5.9/d%, or that 96% of pulse pairs will have a misalignment of less than 11.8/d%. Once again d describes the laser beam diameter (or equally the light sheet thickness) in millimetres. For Laser B, with a beam diameter of 9 mm, this corresponds to a misalignment of 0.7% and 1.3% respectively – a relatively small misalignment. Investigations into laser light sheet misalignment effects (discussed in Chapter 7) suggest there to be a light sheet mismatch threshold, beyond which changes to laser alignment can rapidly influence the correlation of images and the prevalence of spurious vectors. Therefore errors in mean laser beam overlap alignment can easily compound with shot-to-shot beam pointing jitter to cumulatively lower PIV measurement quality. The precise magnitude of this jitter will clearly vary with the laser system, as well as other factors such as the ambient conditions. However, it is nonetheless a behaviour that experimentalists should be aware of when configuring experiments and performing PIV measurements.

6.4 Recommendations for PIV best practice

Despite the multitude of laser-related factors which can confound or obstruct PIV experiments, high quality data can be obtained with the methodical use of laser equipment. Given the results from this study, the following recommendations are made to PIV best practice procedures to optimise the laser start-up sequence and minimise laser transient effects.

1. PIV Nd:YAG lasers should be correctly warmed up to a thermal equilibrium state prior to performing any PIV measurements, experimental alignment or laser overlap changes. Approximately 20 to 30 minutes of laser operation should
be sufficient in most cases to reach this equilibrium. However, a longer warm-up
duration may be required if ambient conditions deviate significantly from laser
design operating conditions.

2. Warm-up can be performed by running the entire laser system (following your
laser manufacturer’s recommended start-up procedure) for the complete sequence.
But from our results, running the flashlamps alone appears to be sufficient for
the laser system to reach a thermal equilibrium.

3. Since the majority of laser drift transients appear in the vertical direction
(although this does vary with the laser system), experimentalists may wish
to consider orienting their light sheet so that the horizontal laser direction is
aligned with the light sheet plane-normal. This will reduce the influence of
warm-up transients on light sheet overlap due to out-of-plane misalignment for
most laser systems.

4. Due to the angular laser changes which cause beam drift, the absolute drift
displacement observed in an experiment’s setup can be reduced by minimising
the laser beam path from the laser unit to the measurement field of view.

5. If user adjustment of the laser beam overlap is available for the laser system,
then careful tuning of the mean laser beam overlap (at thermal equilibrium)
between the two laser cavities can not only improve general PIV correlation,
but also increase robustness against steady state beam pointing jitter.

6. Complete shutdown of the laser system should be avoided during PIV mea-
urements (while clearing camera buffers for example). Flashlamps should
continue operation, while the Q-switch trigger may be stopped during this time
if preferred, for safety and convenience.

6.5 Chapter summary

This analysis has investigated key laser stability factors that can influence PIV
measurements, covering a range of typical PIV laser systems, and spanning a variety
of flashlamp conditions and system ages. The following important results were
concluded from this study:

- Clear evidence demonstrating the importance of correct laser warm-up pro-
cedures has been shown, where lasers can potentially move on the order of
millimetres over a modest beam path before the laser reaches thermal equilibrium. Even a brief and seemingly-innocuous shutdown of the laser system for a few seconds can demand a complete restart of the warm-up procedure.

- Laser flashlamp operation, and the resulting temperature imbalance within the laser chassis, plays a key role in the formation of transient effects.

- The two laser heads within dual cavity lasers, typically used for PIV, display uncoupled characteristics throughout the warm-up cycle. Each laser head also exhibits independent shot-to-shot beam pointing jitter at thermal equilibrium, which can influence PIV light sheet overlap and the quality of subsequent PIV correlations.

- These results have been synthesised into five recommendations for PIV best practice, to maximise the quality of PIV results.

PIV experimentalists should ultimately have an awareness of the nature of these laser stability effects and an understanding of how PIV setup and operational decisions may influence the quality of their results.
Chapter 7

Laser mismatch and misalignment effects on PIV measurements

This chapter incorporates content from the following two publications:


I was responsible for developing and writing Grayson et al. (2018), with input from my supervisors N Hutchins and I Marusic. The experiments documented in this paper were performed with assistance from CM de Silva.


In Scharnowski et al. (2017), I initiated the investigations on this topic and led the experimental validation and comparison of light sheet mismatch, as well as discussions regarding experimental laser mismatch profiling.

The intensity distribution and alignment characteristics of a laser beam can vary over time, due to factors such as ageing system components and the drifting alignment of laser optics. These variations can have a particular impact on laser-based flow visualisation measurements, which rely on stable and uniform laser beam intensity distributions. Measurement techniques which use dual-cavity lasers, such as particle image velocimetry (PIV), are especially vulnerable to these changes, since the characteristics of each laser cavity can drift independently. Mismatch in the behaviour of
Chapter 7. Laser mismatch and misalignment effects on PIV measurements

Figure 7.1: Sketch of laser light sheet intensity distributions, illustrating the equivalence of (A) out-of-plane velocities and (B) out-of-plane misalignment of the laser sheet on the resulting illumination of tracer particles. Blue and red outlines indicate positions under laser pulses 1 and 2, respectively, while black outlines represent unchanged positions over pulses 1 and 2. Solid circles show particles with similar pulse 1 and 2 illumination, while hollow circles represent particles with unequal illumination, such that they have little or no contribution to correlation.

The two laser cavities can degrade the correlation of resulting PIV image pairs, and subsequently impact measured flow quantities. Therefore, quantifying and refining laser overlap and profile distributions can help to improve experimental results, and can be crucial when performing more challenging PIV measurements involving multiple pulses (e.g., 3 or 4 pulse PIV) or large fields of view.

Two misaligned, but otherwise identical light sheets in a PIV experiment have an effect equivalent to an out-of-plane velocity component in the flow (see figure 7.1), increasing the out-of-plane loss of particle pairs under typical flow conditions (Adrian and Westerweel, 2011, Scharnowski and Kähler, 2016a, Scharnowski et al., 2017). Under extreme out-of-plane velocity conditions, this behaviour may even be exploited to minimise out-of-plane loss-of-pairs by deliberately misaligning laser sheets (Kähler and Kompenhans, 2000). A number of studies have investigated the effects of out-of-plane loss-of-pairs on PIV results and the impact on PIV uncertainties (Nobach and Bodenschatz, 2009, Nobach, 2011, Scharnowski and Kähler, 2016a, Scharnowski et al., 2017). However, while out-of-plane velocity components may be unavoidable in a given flow of interest, laser light sheet mismatch can be identified and corrected prior to performing an experiment. This correction of the experimental setup prior to capturing PIV images decreases the error associated with the measurement, yielding higher quality results.

Despite the importance of laser light sheet overlap and the similarity of laser profiles for high quality PIV measurements, careful refinement of laser shape and alignment is sometimes overlooked during the setup of experiments. Experimental papers often neglect any mention of light sheet parameters and behaviour (the quality of light sheet
overlap, for example, which may offer some context to the results), while others may mention a light sheet thickness without any explanation of the measurement method or width criteria used to define what is often assumed to be a Gaussian profile. We note that laser sheet thicknesses can be extracted from stereo PIV measurements (Wieneke, 2005), and tomographic PIV allows an approximation of the laser sheet intensity distribution to be reconstructed (Blinde et al., 2015). In practice, indications of experimental laser overlap quality can also be obtained by capturing two PIV images with a very small time interval (for near-zero particle displacement) and examining the correlation magnitude, or by calculating the correlation/autocorrelation volume ratio from any PIV image pair (Scharnowski and Kähler, 2016a, Scharnowski et al., 2017). However, both of these techniques do not inform the changes which may be necessary to improve the laser overlap performance during laser alignment, nor detail the nature of each light sheet’s intensity distribution. Therefore, from these methods, an experimentalist can learn if they have a light sheet mismatch problem, but they do not know the necessary course of corrective action. A more rigorous approach is required for more detailed measurements of the laser sheet in stereo and tomographic PIV configurations, as well as quantifying any of the laser parameters found in 2D PIV setups.

Some studies do control and specify the laser thickness by employing a fixed-width slit, which can approximate a top hat light sheet profile. Assuming negligible laser beam divergence, the laser sheet thickness is, therefore, equal to the slit width (Scarano et al., 2006, Elsinga et al., 2006b, Blinde et al., 2015). This method, though, does not account for variations in laser intensity distribution or overlap. Laser burn tests can be a useful method of comparing light sheet thickness and estimating sheet separations, as was used in a dual-plane PIV study by Ganapathisubramani et al. (2005). However, burn papers generally offer insufficient resolution and dynamic range to analyse the sheet intensity distribution in detail. Imaging a surface illuminated by a laser sheet can yield further information regarding the intensity distribution. Fond et al. (2015) imaged samples of laser sheets using a piece of paper normal to the laser beam, while Kähler and Kompenhans (2000) and Mistry and Dawson (2014) imaged the sheet on a white plate, inclined relative to the laser sheet for increased resolution. Electronic laser profiling methods are increasingly being used to quantify laser intensity distributions and alignment with greater sensitivity and repeatability. Studies have used a knife edge laser profiler (Mullin and Dahm, 2005), laser profiles of the laser beam prior to manipulation by the sheet optics (Brücker et al., 2012), and camera-based laser profilers for monitoring laser sheet distributions and alignment (Mullin and Dahm, 2005, Pfadler et al., 2009, Naka et al., 2016). Camera-based laser profilers tend to
offer the greatest flexibility with typical pulsed PIV lasers, since they are able to 
easily capture dynamic (shot-to-shot), as well as static, laser beam behaviours.

This study examines the impact of laser sheet misalignment and profile mismatch 
in PIV experiments by first isolating these parameters in simulations of particle 
images, and estimating the sensitivity of laser configurations on PIV measurement 
quality and flow statistics. The streamwise-spanwise plane of a turbulent boundary 
layer is considered in this work, and although some variations in error response are 
expected from different measurement planes and from other fluid flows, similar trends 
in results (and the same general conclusions) would be anticipated. A modular, 
low-cost laser profiling device (described in Chapter 4) is then used to measure and 
compare experimental laser misalignments to the simulated and predicted behaviours 
in a PIV measurement.

Throughout this study, the coordinate system \( x \), \( y \), and \( z \) refers to the streamwise, 
spanwise, and wall-normal directions, respectively. Corresponding instantaneous 
streamwise, spanwise, and wall-normal velocities are denoted by \( u \), \( v \), and \( w \). Overbars 
indicate averaged quantities, and a superscript + refers to normalisation by inner 
scales, for example, \( u^+ = u/U_\tau \) and \( x^+ = x U_\tau / \nu \), where \( U_\tau \) is the friction velocity 
and \( \nu \) is the kinematic viscosity of the fluid.

7.1 Simulating laser sheet mismatch

The effects of laser sheet mismatch can be systematically investigated with the use of 
simulated PIV images. This enables control over all measurement parameters, while 
still considering experimentally realistic flows. Consequently, the variables of interest 
can be isolated and their impacts examined in detail.

7.1.1 Simulation methodology

The simulations performed in this study use the in-house PIV simulation and processing 
MATLAB code detailed in Chapter 3, which was originally developed for tomographic, 
and later 2D planar PIV simulations (see de Silva et al., 2012). The recent software 
modifications outlined in Chapter 3 have allowed more realistic PIV images to be 
generated, including more rigorous modelling of PIV image noise behaviours, and 
varyations in particle shape and size. Crucially, the light sheet profile can also be 
defined, allowing the implementation of Gaussian, top hat and super-Gaussian cross 
sections, in addition to applying custom profiles using data from a laser profiling
camera. The width and alignment of each laser pulse can also be specified, an important feature which enables the mismatch analysis presented in this study.

As described in Chapter 3 and following prior work (de Silva et al., 2012, Worth et al., 2010), the simulation procedure uses DNS velocity fields to displace randomly located virtual particles and generate synthetic PIV particle images. These images are subsequently fed into a PIV processing and correlation code, which applies a 'template matching' normalised cross-correlation scheme based on the work of Lewis (1995) (details regarding the implementation of this scheme can be found in de Silva et al., 2012). The resulting velocity fields can be directly compared to the input DNS velocity fields and errors can be calculated. Using this method, the degree of laser light sheet overlap can be systematically varied and comparisons between the resulting synthetic PIV velocity fields can be made.

7.1.2 Simulation parameters

For the present study, the turbulent boundary layer DNS data set from Sillero et al. (2013) at $Re_\theta = 6500$ is used. Synthetic two-pulse particle images are generated over a streamwise-spanwise plane using the parameters summarised in table 7.1, with simulations repeated for Gaussian, super-Gaussian, and top hat light sheet profiles. Infinite depth of field and no image noise is modelled in this simulation, while experimentally representative particle densities, sizes, and size variations are used. A multipass correlation algorithm with window deformation is applied to process the resulting synthetic images from a 64 × 64 pixel interrogation window down to a final interrogation window size of 32 × 32 pixels, or approximately 20 × 20 viscous units. Results are averaged over ten distinct DNS flow fields, as well as over cases that interchangeably misalign pulse 1 (with pulse 2 fixed), and misalign pulse 2 (with pulse 1 fixed), to avoid biasing effects.

The Gaussian and super-Gaussian light intensity profiles, $I_0(z)$, across the light sheet-normal direction $z$, are modelled by equation 7.1, using $N = 2$ and $N = 10$ respectively.

**Table 7.1: Summary of simulation parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement plane</td>
<td>Streamwise × spanwise</td>
</tr>
<tr>
<td>$Re_\theta$</td>
<td>6500</td>
</tr>
<tr>
<td>DNS domain ($x^+ × y^+$)</td>
<td>4200 × 6300</td>
</tr>
<tr>
<td>Wall-normal height ($z^+$)</td>
<td>240</td>
</tr>
<tr>
<td>Image resolution</td>
<td>1.6 viscous units/pixel</td>
</tr>
<tr>
<td>Image bit-depth</td>
<td>16 bit</td>
</tr>
</tbody>
</table>
In this expression, \( I_{\text{max}} \) describes the maximum intensity of the profile, while \( z_0 \) refers to the midpoint of the light sheet distribution and \( \sigma \) denotes the profile’s standard deviation. The width of the simulated top hat light sheet profile is matched to the Gaussian profile standard deviation, \( \sigma \), and the resulting three profiles are illustrated in figure 7.2.

\[
I_0(z) = I_{\text{max}} \times \exp \left[ -\frac{1}{2} \left( \frac{z - z_0}{\sigma} \right)^N \right] \quad (7.1)
\]

Two separate laser mismatch scenarios are considered. In case 1, two identical light sheet profiles are systematically translated relative to one another, as shown schematically using Gaussian profiles in figure 7.3a. This scenario is directly equivalent to the presence of an out-of-plane flow velocity component. The light sheet thickness used in this simulation case remains fixed, with a standard deviation of 7.1 viscous units. This thickness was determined by performing a Gaussian fit onto a representative experimental light sheet profile. Light sheet misalignment is simulated in scenarios ranging from perfect overlap to a shift equivalent to a 3\( \sigma \) light sheet offset.

Case 2 investigates the impact of different light sheet widths on PIV performance, as shown in figure 7.3b. In this scenario, both laser pulses remain centred about a fixed location, but the standard deviation of one light sheet profile (from one laser pulse) is varied, while the other light sheet profile (from the other laser pulse) remains fixed. Scenarios have been simulated with laser profile standard deviations ranging from 0.4 viscous units to 7.1 viscous units, while the fixed light sheet profile uses a constant standard deviation of 7.1 viscous units. Therefore, the mismatched case always has a narrower laser sheet profile than the reference 7.1 viscous unit standard deviation case.
Chapter 7. Laser mismatch and misalignment effects on PIV measurements

Case 1 shift misalignment

Case 2 width mismatch

Figure 7.3: Sample (A) case 1 shift misalignment and (B) case 2 width mismatch, applied to Gaussian light sheet profiles. The blue curve illustrates the intensity profile of laser pulse 1, while the red curve represents the intensity profile of laser pulse 2.

7.1.3 Quantification of laser mismatch

To compare the results of cases 1 and 2 on a common set of axes, a metric is needed to quantify the mismatch of successive laser pulses. Early work on out-of-plane loss-of-pairs by Keane and Adrian (1992) established a parameter, $F_O$, defined by equation 7.2. This loss-of-correlation factor estimates the reduction in correlation peak height due to out-of-plane loss-of-pair effects – either from out-of-plane motions or laser mismatch. $I_{01}$ and $I_{02}$ represent the light sheet intensity profiles of laser pulses 1 and 2, respectively, while $z_{01}$ and $z_{02}$ indicate their sheet centre locations and $\Delta z$ denotes the out-of-plane particle displacement (considered to be zero in this analysis due to averaging to isolate mismatch effects). $F_O = 1$ corresponds to when every particle found in two successive PIV images can be paired together, while $F_O = 0$ indicates that no particles can be paired from the image set. Intermediate values reflect partial pairing of particles.

$$F_O = \frac{\int I_{01}(z - z_{01}) \cdot I_{02}(z - z_{02} - \Delta z) \, dz}{\int I_{01}(z) \cdot I_{02}(z) \, dz}$$

(7.2)

The $F_O$ parameter offers a good measure of singular out-of-plane velocity and light sheet-normal laser misalignment effects, which serves its original, intended purpose. However, this parameter does not capture other scenarios, such as when laser sheet profiles have differing widths, as applied in case 2 of this study. Therefore, a modified form of $F_O$, shown in equation 7.3, was developed in collaboration with Sven Scharnowski and Christian Küehler from Bundeswehr University, Munich, to better quantify variations in laser mismatch. This revised $F_O$ parameter was first proposed and assessed by Scharnowski et al. (2017), and is applied throughout this study. By modifying the denominator, contributions of all particles within the light sheets are
now treated in the same way as in the calculation of the cross-correlation function. The adjustment to the $F_O$ expression has no impact on the calculation of out-of-plane velocity effects for identical light sheet profiles, while enabling laser profile width and shape mismatches to also be distinguished.

$$F_O = \frac{\int I_{01}(z - z_{01}) \cdot I_{02}(z - z_{02} - \Delta z) \, dz}{\sqrt{\int I_{01}^2(z) \, dz \cdot \int I_{02}^2(z) \, dz}} (7.3)$$

### 7.1.4 Quality of correlation

Using the revised expression for $F_O$ to generalise the mismatch conditions applied in these simulations, the impact on correlation quality can be assessed under different laser alignment scenarios. Figure 7.4a shows the average correlation coefficient ($\bar{R}$) from both simulation cases 1 and 2, which is calculated by averaging together the correlation coefficients from each final interrogation window of the raw velocity fields. The scales above each plot in figure 7.4 show the case 1 and 2 Gaussian profile mismatch required for a range of $F_O$ values. Case 1 mismatch is indicated by the magnitude of the light sheet offset, normalised by the standard deviation of the light sheet profile (case 1 considers identical light sheet widths). Case 2 mismatch is shown by the ratio between the standard deviations of the thick and thin light sheets. We note that the maximum average correlation remains below 0.8 due to the turbulent DNS flow field used in this simulation, the experimentally representative particle size and density parameters applied to the synthetic images, and other sources of error from PIV processing. The three tested laser profile shapes exhibit similar behaviour in figure 7.4a, showing steady, near-linear degradation of mean correlation coefficient for both shift and width mismatch simulations (cases 1 and 2 respectively), until excessive mismatch flattens the mean correlation at the correlation noise floor. Case 2 simulations produce a higher noise floor than found with case 1, due to reduced particle image densities from the narrowing of one light sheet. The revised $F_O$ expression is able to distil consistent behaviour from shift and width misalignments, despite complex interactions under these scenarios influencing the particle image pairs, interrogation window particle image densities, and variations in particle image intensities.

Outlier detection can be performed on the simulation results from both cases 1 and 2, like any typical PIV experiment data, to check for and remove spurious vectors. To this end, the normalised median test of Westerweel and Scarano (2005) is applied to these results, using the same recommended parameters for all scenarios. The resulting percentage of spurious vectors detected from the velocity vector fields in different laser sheet shift and width mismatch simulations are plotted on linear-log axes, as shown in
Chapter 7. Laser mismatch and misalignment effects on PIV measurements

Figure 7.4: Simulation results illustrating the impact of laser profile mismatches on (a) average correlation coefficient and (b) the proportion of spurious vectors. Case 1 shift mismatch results are shown using solid lines, while case 2 width mismatch results are shown with dashed lines. Additional scales above each plot correspond to the magnitude of case 1 light sheet offset, normalised by the standard deviation, and the case 2 light sheet width ratio for Gaussian light sheet profiles.
The results show that both case 1 and 2 simulations with moderately high \( F_O \) values (\( F_O > 0.65 \)) contain few spurious vectors, consistent with their reasonably well aligned and matched laser profiles. However, the proportion of spurious vectors detected by the normalised median test increases rapidly for values of \( F_O \) less than 0.65. This \( F_O \sim 0.65 \) threshold is universally observed under both shift (case 1) and width (case 2) mismatch scenarios for all tested light sheet profile shapes. The limit of \( F_O \sim 0.65 \) corresponds to simulations with shift offsets ranging from 1.35\( \sigma \) for a Gaussian sheet profile, up to 2.4\( \sigma \) for a super-Gaussian profile, or when the width of one laser sheet is between 2.4 (for a top hat profile), and 4.3 (for a Gaussian profile) times greater than the other. A light sheet width mismatch, where one light sheet is more than twice as wide as the other may be readily identified using a variety of laser measurement techniques, and may even be observed with a quick visual check of the laser. Meanwhile, a 1.35\( \sigma \) shift offset of two laser profiles is more subtle and detection is likely to require more rigorous laser profiling. This reinforces the zero-displacement synthetic image results presented in Scharnowski et al. (2017), and highlights that \( F_O \) and measurement quality are more sensitive to out-of-plane laser alignment than to mismatches in light sheet width.

For experiments with a laser sheet thickness on the order of 1 mm, an offset of only 0.35 mm is sufficient to degrade \( F_O \) to 0.65 (assuming a top hat profile). A laser sheet misalignment of this order under experimental conditions may be difficult to identify and correct using visual alignment methods, burn tests or other techniques unable to capture the light sheet’s intensity distribution in detail. Furthermore, very small changes in laser sheet mismatch around the spurious vector threshold for each case, either from changes to the laser’s optical configuration or from subtle shot-to-shot laser instability (see Chapter 6), can have large consequences for the proliferation of spurious vectors. For example, changing \( F_O \) from 0.5 to 0.4 can increase the proportion of detected spurious vectors from 3.7\% to 14.8\%, and only involves an increase in the pulse shift from 1.65 to 1.95\( \sigma \) (or an additional misalignment of 0.05 mm for a 1 mm thick laser sheet). A misalignment of this magnitude could, therefore, be the difference between noisy, but acceptable PIV measurements, and effectively unusable data sets.

To further illustrate the impact of laser misalignment, figure 7.5 presents raw instantaneous streamwise velocity fields. Case 1 simulations using a Gaussian light sheet profile are compared with \( F_O \) values of \( F_O = 0.95 \) (near ‘ideal’, or a shift of 0.45\( \sigma \)), \( F_O = 0.51 \) (just past the spurious vector threshold), and \( F_O = 0.28 \) (well beyond the spurious vector threshold). While the \( F_O = 0.95 \) velocity field appears visually smooth, a scattering of clear outliers becomes visible once \( F_O = 0.51 \). Closer analysis of these raw instantaneous fields using the probability density function of the streamwise
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Figure 7.5: Comparison of raw instantaneous streamwise velocity fields from case 1 simulations with a Gaussian light sheet profile. Streamwise and spanwise dimensions are denoted by $x$ and $y$ respectively.

Figure 7.6: Comparison of the streamwise velocity error probability density function from the case 1 Gaussian instantaneous velocity fields shown in figure 7.5. The raw velocity fields generate error distributions shown by the solid lines, while velocity errors after the application of the normalised median test are shown by the open circles.

Velocity error (shown in figure 7.6) also reveals the presence of additional noise in the $F_O = 0.51$ velocity field that is not detected by the normalised median test (the error p.d.f. of each velocity field after the application of the median test is shown by the open circles). This noise increases the observed streamwise velocity error, broadening the error distribution and consequently lowering the p.d.f. peak. Therefore, even if the clearly spurious vectors are removed from this field, fine scale noise due to poor
laser overlap continues to degrade a measurement’s accuracy. At the point $F_O$ reaches 0.28, the velocity field is practically unusable due to the high density of spurious vectors. Note that while the tails of the p.d.f. results in figure 7.6 have been clipped to emphasise the peak behaviour of interest, a highly spread distribution of spurious vectors are observed with streamwise velocity errors beyond $\pm 10\%$ (particularly in the $F_O = 0.28$ case).

**7.1.5 Errors in flow statistics**

It is worth noting that even though we do not see a sharp increase in the number of spurious vectors until $F_O < 0.65$, the sensitivity of a measurement’s laser misalignment can depend on the flow statistics of interest. Figure 7.7 shows the percentage error associated with streamwise mean velocity and turbulence intensity statistics, after spurious vectors have been removed via the normalised median test. Case 1 and 2 simulations and all tested light sheet profile shapes exhibit consistent error behaviour. Predictably, the mean velocity measurement has a lower baseline error at $F_O = 1$ compared with turbulence intensity, which is a higher order statistical measure. What is more revealing, however, is a comparison of the breakpoints in these statistics, after which the error grows more rapidly. The turbulence intensity jumps to higher errors at a greater $F_O$ value (around $F_O \sim 0.6$) than observed in the mean velocity (approximately $F_O \sim 0.5$).

To further investigate these trends, the error results from each simulation case were averaged together for improved convergence, due to their relatively consistent behaviour. The resulting error averages for the streamwise mean, variance (turbulence intensity), skewness and kurtosis statistics are shown in figure 7.8a on linear axes, normalised by their error under ‘ideal’ overlap conditions ($F_O = 1$). The error breakpoints exhibit a clear trend towards higher $F_O$ values when considering higher order flow statistics. To quantify this trend, the $F_O$ corresponding to a given increase in a statistic’s error (eg: a doubling in error, or a $\times 2$ factor) was recorded. This process is equivalent to the intersection between the normalised error of the flow statistic and a horizontal line at 2% normalised error for a $\times 2$ error criterion. Three maximum error criteria were considered for comparison ($\times 1.5$, $\times 2$ and $\times 3$ factors), and the corresponding $F_O$ thresholds for each flow statistic are shown in figure 7.8b. Results suggest that the lowest $F_O$ achievable under these criteria can range from $F_O = 0.5$ for mean velocities, up to $F_O = 0.7$ for kurtosis. This defines a lower limit for $F_O$, but higher $F_O$ values are clearly desirable for greater margin in laser and error performance. It is, therefore,
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Figure 7.7: Errors associated with (A) streamwise mean velocity ($\bar{U}$) and (B) turbulence intensity ($\overline{u'^2}$). Case 1 shift mismatch results are shown using solid lines, while case 2 width mismatch results are shown with dashed lines.
Figure 7.8: (A) Averaged streamwise flow statistic errors (normalised) from all simulation cases. The dotted horizontal line at 2% normalised error illustrates the ×2 error criterion, one of three criteria applied to find the FO thresholds shown in figure 7.8b. (B) FO thresholds corresponding to each nth central moment of the averaged streamwise flow statistics.
evident that the measurement quality and quantities of interest can determine the importance of maintaining good matching of successive laser profiles (and thus a high $F_O$ value). As would be expected, higher order flow statistics can display greater sensitivity to laser mismatch, with inferior robustness to low $F_O$ values when compared with lower order statistics (mean flow, for example).

### 7.1.6 Impact of seeding density

Figure 7.9 shows the effect of different seeding densities ($N_{ppp}$) on the correlation coefficient and spurious vector proportion of case 1 and 2 Gaussian profile simulations. These simulations consider PIV images with seeding half as dense ($0.5N_{ppp}$), and twice as dense ($2N_{ppp}$) as the simulations presented previously in section 7.1.

Case 1 simulations display behaviours consistent with conventionally seeded results for both correlation coefficient and spurious vector detection, although higher seeding scenarios result in the detection of marginally fewer spurious vectors. In addition, it is important to note that case 1 shift mismatch simulations maintain constant seeding densities in simulation images, even under severe misalignment, since the width and shape of the light sheets remain unchanged. Case 2 width mismatch scenarios, in contrast, consider one light sheet that becomes narrower than the other, which consequently reduces the seeding density in the PIV image corresponding to the narrower light sheet at lower $F_O$ values. This explains why, in figure 7.4b of section 7.1.4, case 2 spurious vectors deviate slightly from case 1 results at low $F_O$.

When adding further reductions to seeding density ($0.5N_{ppp}$), greater deviation from spurious detection trends at low $F_O$ is observed due to severe narrowing of one light sheet pulse. However, in these $0.5N_{ppp}$ cases, with even moderate width mismatch, the reduction in seeding density reaches extreme levels that would be considered unrealistic in any carefully conceived PIV measurement. Similar case 1 and 2 behaviours are also observed in the streamwise mean and turbulence intensity error (not shown), with deviations only found in case 2 simulations at low $F_O$. In summary, our results suggest that under typical PIV measurement conditions, changes to seeding density do not have any significant impact on the sensitivity to laser mismatch.

### 7.1.7 Other considerations

Image pre-processing techniques were also investigated for their impact on the sensitivity to laser mismatch, where min-max filtering (Westerweel, 1993) and histogram equalisation (Adrian and Westerweel, 2011) algorithms were considered. However, image pre-processing operates by normalising particle image intensities (determined
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Figure 7.9: Effect of different seeding densities, $N_{ppp}$, on (A) average correlation coefficient and (B) the proportion of spurious vectors. Different $N_{ppp}$ are compared using case 1 and 2 Gaussian simulations, where case 1 shift mismatch results are shown using solid lines, while case 2 width mismatch results are shown with dashed lines. Case 1 and 2 top hat and super-Gaussian simulations are shown by solid grey lines for reference.
by the algorithm input parameters), thereby increasing the uniformity of the image and making the effective light sheet intensity distribution more “top hat-like”. In this process, the effective thickness of the light sheet contributing to correlation is also increased (along with any associated spatial attenuation over the light sheet-normal direction). By artificially altering the light sheet intensity distribution in this way, the actual light sheet intensities $I_{01}$ and $I_{02}$ used in the calculation of $F_O$ (equation 7.3) are no longer representative of effective light sheet mismatch conditions, and equation 7.3 underestimates the effective $F_O$ of the PIV image pair. Simulations verify this limitation, where image pre-processing applied to top hat profile scenarios (which has a limited impact on images, since the profile is already a uniform top hat) show consistent behaviours with prior results (see figure 7.10). Meanwhile, the results from Gaussian profile scenarios with image pre-processing exhibit the same kind of degradation in correlation coefficient and increase to errors and spurious vectors, but these responses have been shifted to lower $F_O$ values when calculated using equation 7.3 (highlighted by the arrow annotation in figure 7.10). Appropriate correction of the $F_O$ equation for use with image pre-processing, or the direct calculation of $F_O$ from processed PIV images (Scharnowski and Kähler, 2016a, Scharnowski et al., 2017) should generalise behaviours in pre-processing scenarios, but is beyond the scope of this work. Image pre-processing, therefore, has the potential to increase robustness to laser mismatch after PIV images have been captured, but the effectiveness of these
algorithms can depend on the uniformity of the actual laser profiles, as well as the extent of PIV image noise and artefacts. Appropriate tuning of a PIV experiment’s laser mismatch prior to image capture will always result in superior measurements, since they involve a fundamentally higher quality data set that is less dependent on processing algorithm performance.

Some outlined light sheet mismatch scenarios can be readily identified using a variety of laser alignment techniques. However, undertaking a challenging PIV measurement configuration can demand increased care and precision in light sheet alignment and matching, which may require detailed, quantitative laser profiling to balance various experimental compromises. For example, highly spread light sheets are necessary in PIV measurements over large fields of view, where variations in each laser’s beam profile can translate to changes in light sheet mismatch over the measurement domain (such as the variations found in figure 5.8 and discussed in section 5.2.1). Any adjustments to the light sheet, to improve the light sheet overlap in the centre of the field of view, for example, must balance with the impacts on overlap elsewhere in the field of view. Similarly, multiple pulse PIV may require the alignment of multiple PIV laser systems, and depending on the correlation algorithm employed, this configuration may be more sensitive to laser mismatch (due to an additive mismatch effect). These laser misalignment sensitivities to multipulse PIV are further investigated in Chapter 9. Refinement of light sheet profile mismatch can, therefore, be critically important to the quality of many PIV measurements.

7.2 Experimental laser misalignment

To complement and validate the simulation results outlined in sections 7.1.4 and 7.1.5, a PIV experiment has been performed involving the deliberate mismatch of the laser light sheet.

7.2.1 Experimental configuration

Two-pulse, 2D PIV measurements were taken of a $Re_\theta = 7500$ (approx.) turbulent boundary layer in the High Reynolds Number Boundary Layer Wind Tunnel (HRN-BLWT) at the University of Melbourne, illustrated in figure 7.11 (for further details regarding this facility, see Nickels et al., 2005). In order for comparisons to DNS data, this experiment was performed approximately 5 m downstream of the boundary layer trip, at a freestream velocity of $\sim 10 \text{ m/s}$. Data were captured in the streamwise-spanwise plane (see figure 7.12) over a region measuring $4200 \times 6300$ viscous units.
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Figure 7.11: Schematic of the High Reynolds Number Boundary Layer Wind Tunnel (HRNBLWT) at the University of Melbourne

(or 175 mm × 265 mm, streamwise × spanwise), and at a wall normal height of approximately 240 viscous units (∼10 mm). The laser light sheet was produced using a Spectra-Physics Quanta-Ray PIV-400 pulsed 532 nm Nd:YAG laser (nominally at 400 mJ/pulse), over a 9.35 m beam path. To generate the necessary illumination along the wall-parallel plane, the final mirror in the beam path was placed inside the working section of the wind tunnel, 2.5 m downstream of the measurement region (in figure 7.12). Earlier experiment campaigns with this mirror mounting configuration have used hot wire anemometry measurements to verify that the separation between the wind tunnel mirror and PIV measurement region is sufficient to avoid any blockage effects influencing PIV data (de Silva et al., 2015, and others). This mirror was also pitched downward slightly in an effort to compensate for the streamwise growth of the boundary layer and maintain the laser sheet at a constant wall normal height in viscous units.

PIV images were captured using a single 10.7 megapixel PCO 4000 PIV camera and a Nikon AF Micro-Nikkor 60 mm 2.8D lens, providing an image resolution of 2672 × 4008 pixels (streamwise × spanwise) and a flow resolution of approximately 1.6 viscous units/pixel. The camera was oriented normal to the streamwise-spanwise plane, and a glass plate containing a printed dot grid was used for image calibration. A sample PIV image from the camera is shown in figure 7.13. Note that the experimental field of view and spatial resolution in viscous units are effectively identical to that considered
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Figure 7.12: Sketches of the experimental setup (A) top view, and (B) side view. Annotations denote: 1 the Nd:YAG laser system, 2 mirror mounted within wind tunnel working section, 3 PIV camera.

Figure 7.13: Sample PIV experiment image (left), and image detail (right). Fluid flow in this image is observed from left to right.
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Figure 7.14: Sample streamwise velocity field from experiment setup

by the simulations, outlined in section 7.1 (with only negligible variations between the two cases). Seeding in this measurement was provided by DEHS (di-ethyl-hexyl-sebacate) droplets and image pairs were captured with a time interval of $\Delta t = 110\mu s$, corresponding to a mean pixel displacement of $\sim 11$ pixels. Light sheet intensity profiles were captured using the low-cost laser profiling camera design outlined in Chapter 4. The same multipass correlation algorithm with window deformation used in section 7.1 was applied to process these experimental images, with initial interrogation windows of $64 \times 64$ pixels, and a final window size of $32 \times 32$ pixels. $U_\tau$ was calculated by applying the composite profile from Chauhan et al. (2009) to the dataset. A sample streamwise velocity field resulting from this process is shown in figure 7.14, where fluid flow is observed from left to right.

Deliberate misalignment of the laser light sheets was possible thanks to the readily accessible beam combining optics in the front of the Spectra-Physics laser unit used in this experiment. Measurements were taken by misaligning the laser beam using the laser’s adjustable combining optics, and then allowing the laser to stabilise for a period of time prior to acquiring PIV images (to ensure the laser is at thermal equilibrium – for further discussion of the thermal equilibrium impacts on PIV laser operations, see Chapter 6). While operating the wind tunnel at a reduced speed for safety reasons, multiple laser profiles of the light sheet (to average laser jitter effects) were captured at the centre of the experimental field of view. The wind tunnel was then returned to the measurement velocity and allowed to stabilise, before capturing a set of 120 PIV image pairs. This process was repeated for eight distinct laser alignment and mismatch combinations. Figure 7.15 shows a selection of the resulting laser profiles,
7.2.2 Experimental results

The average correlation coefficient for the experimental data set is plotted with black triangle (△) symbols, as shown in figure 7.16a. While the simulations in section 7.1 (also shown in figure 7.16a with the grey lines) isolate light sheet mismatches of profile width, or alignment in distinct scenarios, experimental light sheet profiles involve combinations of alignment, width and shape mismatches (clearly observed in figure 7.15). Therefore, the experimental data presented here combine shift and width mismatches, as well as incorporating unsimulated mismatches in the shape of each light sheet intensity profile (which are beyond the scope of this study). Despite these complex interactions in the experimental results, the gradient at which the correlation coefficient degrades is consistent with earlier idealised simulation results, as presented in section 7.1. The small offset observed between the correlation coefficient of the experiment and idealised simulation results is due to systematic differences in the image and correlation noise of these data sets. To confirm the cause of this offset, simulations rigorously matched to the experimental laser sheet profile and noise conditions were also performed, and are discussed in section 7.2.3.

The proportion of spurious vectors resulting from these experiments are also compared with simulations in figure 7.16b, using common normalised median test parameters. While some scatter can be observed in the experimental results, many additional experimental errors can cause or influence the spurious vectors detected in a PIV measurement. Nevertheless, a similar baseline proportion of spurious vectors under
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Figure 7.16: Experiment and simulation results of laser profile mismatch on (A) average correlation coefficient and (B) the proportion of spurious vectors

‘ideal’ \( (F_O \sim 1) \) overlap conditions can be observed in experiment and simulation results. Furthermore, a rapid increase in experimental spurious vectors can be observed at an approximately similar \( F_O \) to that predicted by the simulations.

Due to the methodology of this experiment, the wind tunnel speed was reduced between the capture of each PIV image set to profile the laser light sheet. Consequently, small variations in wind tunnel speed were introduced between each measurement, making the direct comparison of experimental and simulation mean statistics difficult. However, a comparison of the streamwise turbulence intensity (shown in figure 7.17), normalised by the turbulence intensity under ‘ideal’ overlap conditions, shows reasonably good
agreement in behaviour, with data exhibiting similar $F_O$ thresholds beyond which the turbulence intensity rapidly increases.

### 7.2.3 Experiment-matched simulations

The simulation results from section 7.1 can be further validated by running revised synthetic PIV simulations matched to the noise conditions observed in the experiment, using the parameter matching procedure outlined in Chapter 3. While this matching is not necessary to compare the overall behaviour of the experimental results to simulations, it can verify the sensitivity of quantities to noise levels (e.g., the correlation coefficient). To this end, the experimental light sheet intensity profile from each laser head is captured with the laser profiling camera at the centre of the measurement field of view (as shown in figure 7.15), and rescaled for application to the simulation’s illumination model. Dark field images from the PIV camera are also acquired to determine the background noise characteristics of the camera sensor, which defines the Gaussian noise distribution parameters applied to the simulation. Several additional simulation parameters are then iteratively tuned via comparative image measures to achieve close matching to an individual experimental PIV measurement.

As outlined in depth in Chapter 3, the first comparative metric examines the average seeding particle diameter by autocorrelating interrogation windows over each of the experimental and simulation images, and averaging the results (also outlined in Adrian and Westerweel, 2011). This measure helps to match the simulation’s particle diameter, and also the range and distribution of variations to particle diameter, by first considering the sharpest region of the experimental images (normally the centre...
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Subsequently processing the entire image can account for particle diameter changes due to localised image focus variation and loss of sharpness at the corners of the PIV images, which can then be approximated by the simulation. Using this procedure, a cross-sectional comparison of a resulting experiment-matched autocorrelation peak is shown in figure 7.18a, averaged over the entirety of each image.

The second comparison investigates the distribution of pixel intensities throughout each image (first used by Westerweel, 2000). This plot allows tuning of the maximum simulation particle intensity, background noise and particle density, as well as further refinement of the loss of sharpness characteristics at the image edges (see Chapter 3 for further details). Figure 7.18b shows a sample comparison between pixel intensity distributions from an experiment and experiment-matched simulation.

Experiment-matched simulations, defined using this procedure, are tuned using experimental data and are compared with the PIV measurements in figures 7.16 and 7.17 (the matched simulations are indicated by the red circles, ⬤). Due to minimal changes in the configuration of the experimental setup, changes to the input light sheet profiles were the only necessary modification to simulation parameters across the tested scenarios – all other simulation parameters remained unchanged. Therefore, all variations to the correlation coefficient, spurious vector proportion, and streamwise turbulence intensity of the experiment-matched simulations are a direct result of different laser sheet profile alignment, mismatch and shape.

![Figure 7.18](image.png)

**Figure 7.18:** (A) Average particle radius comparison of sample experimental and experiment-matched simulation distributions. (B) Normalised pixel intensity comparison of sample experimental and experiment-matched simulation histograms. Note that this figure can also be found in Chapter 3 of the image.)
The comparison between the correlation coefficient of the experiment and matched simulations in figure 7.16a show good agreement, with only a slight scatter observed in the experimental results – likely to be caused by small variations in other experimental conditions and errors which may not be captured by the average experimental image characteristics. Resultant biasing, from an experiment’s local changes in light sheet characteristics for example, can even allow the performance of some experimental data points to exceed that of the simulation. Reasonably similar behaviour is also observed in comparisons of the spurious vector proportion (figure 7.16b) and streamwise turbulence intensity (figure 7.17). What is perhaps more revealing however, is that despite the extensive matching of simulation noise parameters and complex light sheet profiles to the experiment, the matched simulations show very similar behaviour to the idealised simulations presented in section 7.1 (correlation coefficient offset excepted, due to fundamental differences in noise). Therefore $F_O$ and these trends in measurement quality are relatively robust to a variety of complex and interacting laser mismatch conditions, including combinations of laser shift, width and shape mismatches. This matched comparison, therefore, validates the simulations presented in section 7.1, confirming their robustness to experimentally realistic conditions and variations. They demonstrate that changes in light sheet alignment and profile width can have significant impacts on PIV image correlation and experimental results.

7.3 Measuring out-of-plane loss-of-correlation

7.3.1 Laser profiling

Simulation and experimental results have demonstrated that out-of-plane light sheet mismatch can have severe consequences on the correlation quality of a measurement. Therefore, quantifying and minimising these effects, especially when aided by high resolution laser profiling devices, can be an important procedure during the setup of an experiment.

Iterative tuning of the light sheet thickness and offset can be achieved via the light sheet optics (which applies equal width change to both light sheets), and the laser system beam combining optics, respectively, for improved $F_O$. However some mismatches in light sheet width, as well as differences in shape factor, can be dictated by the fundamental beam profile behaviour of each laser cavity and may be difficult to correct. While substitution of the laser system with a better performing unit may bypass these concerns, this is rarely a practical solution. Since such width and shape factor characteristics tend to vary over the spread of the light sheet, regions
Figure 7.19: Examples of different light-sheet pairs with optimised overlap. The given $F_O$ is based on zero out-of-plane motion, while $I_{1,2}$ and $z$ parameters are shown in arbitrary units (a.u.)

of superior matching in shape factor and width may be identified and aligned with the measurement field of view. This detailed examination over the full spread of the light sheet (such as figure 5.8 in Chapter 5) will likely require the resolution of a laser profiling camera, but such a technique can maximise the $F_O$ for a given experiment.

Once the best compromise in light sheet width and shape mismatch is achieved, the alignment of the light sheet profiles can be refined and optimised, assuming zero out-of-plane motion. This involves adjusting the alignment of the two cavities of a PIV double pulse laser, using the laser’s beam combining optics. Given the presence of beam pointing jitter in laser systems, which generates shot-to-shot variation in laser beam location and overlap, the light sheet overlap should be calculated as an average from several measurements following sufficient warming of the system (see Chapter 6). Figure 7.19 shows various idealised examples illustrating light-sheet pairs with optimised overlap. For symmetric profiles with a single peak, as shown on the top row of the figure, the best overlap is achieved if the light-sheet centres fall on top of each other. In this case, the value of $F_O$ depends mainly on the variations in shape and width. If the light-sheet profiles are skewed or contain multiple local maxima,
the optimum overlap position might be less obvious, as sketched in the middle and lower rows of figure 7.19.

### 7.3.2 Correlation/autocorrelation volume ratio

Due to the equivalence of out-of-plane velocity and laser misalignment effects (see figure 7.1), quantifying laser mismatch alone does not provide the complete picture of factors influencing the out-of-plane loss-of-correlation in a measurement. Out-of-plane velocity components in a studied flow can also reduce the correlation quality in a measurement, but are not accounted for in profiling camera-based laser mismatch data. However, the establishment of a well-matched light sheet baseline under zero out-of-plane velocity conditions (using a profiling camera) is necessary before introducing any further corrections for out-of-plane velocity effects.

While a mean estimate of out-of-plane flow quantities can be used to approximate the necessary overlap adjustment required, this can be a relatively crude approach which also requires prior knowledge of the flow of interest. A more comprehensive means of correcting for out-of-plane flow velocities involves an analysis of sample PIV images captured from the experimental setup, thereby considering the cumulative impact of laser and out-of-plane velocity effects under non-zero and non-uniform in-plane displacements. Scharnowski and Kähler (2016a,b) have outlined a correlation/autocorrelation volume ratio technique using PIV image pairs which calculates the $F_O$ factor, and incorporates both laser mismatch and out-of-plane velocity effects (see also Scharnowski et al., 2017). This approach recognises that under out-of-plane velocity or laser mismatch scenarios, there is a decrease in the correlation peak height, while the autocorrelation peak remains unchanged. The ratio of volumes beneath the correlation and autocorrelation functions yields $F_O$ (although corrections to the volume calculation are required in the presence of image noise, see Scharnowski and Kähler, 2016b). Since this technique only requires PIV image pairs, it can also be applied retrospectively to previous PIV datasets to quantify $F_O$, and also to help troubleshoot and isolate any causes of degradation in PIV results throughout an experiment.

### 7.3.3 Experimental validation of $F_O$ quantification methods

The 2D, two pulse PIV experiment outlined in section 7.2.1 was also used to validate and compare the results from these two $F_O$ quantification methods. Figure 7.20a shows a sample flow field under one of the measured misalignment scenarios (the flow direction is from left to right), where colour contours indicate the streamwise
velocity. The instantaneous flow field exhibits elongated coherent structures of different velocities which extend along the streamwise direction. Figure 7.20b shows the corresponding instantaneous distribution of $F_O$ estimated from the correlation/auto-correlation volume ratio by using $128^2$ pixel interrogation windows with 50% overlap. A general trend of decreasing $F_O$ from top to bottom is clearly visible in the figure. Although optical camera effects and seeding also play a role, this trend is primarily caused by a decreasing overlap of the light sheets from top to bottom, as shown in figure 7.21 for three $y$ locations of the field of view.

Moreover, the $F_O$ distribution in figure 7.20b features local fluctuations which are caused by loss-of-pairs due to out-of-plane motion (something which cannot be identified with a laser profiling camera). At $70 \, \text{mm} \leq y \leq 80 \, \text{mm}$ for example, a turbulent flow structure of low momentum (dark blue in figure 7.20 on the left) causes an increase in $F_O$ from $\approx 0.6$ to values above 0.9. In this region, fluid is transported away from the wall and the out-of-plane motion of the particles is partly compensated by the offset between the light sheets (see figure 7.21). In other regions $F_O$ is reduced

\begin{center}
\includegraphics[width=0.4\textwidth]{streamwise_u}
\includegraphics[width=0.4\textwidth]{f_o_estimated}
\end{center}

Figure 7.20: (A) Example of the instantaneous distribution of the streamwise velocity in a wall-parallel plane of a turbulent boundary layer and (B) the corresponding $F_O$ estimated from the correlation volume ratio. The light-sheets were intentionally misaligned to study the effect of $F_O$ on the velocity estimation. The approximate spanwise measurement locations of the light-sheet profiles shown in figure 7.21 are given by the dashed lines.
Figure 7.21: Light-sheet intensity profiles for three different spanwise locations corresponding to the PIV measurements shown in figure 7.20.

due to motion of the particles towards the wall. If the resolution needs to be improved by reducing the interrogation window size, the light-sheet overlap must be optimised.

Figure 7.22 illustrates how the interrogation window size affects the estimation of the velocity fluctuations. Modest, but consistent increases in the streamwise velocity fluctuations can be observed throughout the field of view using smaller interrogation window sizes, due to improved spatial resolution. However, smaller windows also cause significant deviations from the velocity fluctuations trend at the bottom edge of the field of view, which coincides with lower experimental $F_O$. This behaviour is observed at $y < 50$ mm with $32^2$ pixel windows, and at $y < 150$ mm for $16^2$ pixel
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Figure 7.22: Estimated streamwise velocity fluctuations as a function of the spanwise location for different interrogation window sizes. The light-sheet overlap degrades for decreasing $y$ as shown in figures 7.20b and 7.21 windows. The $16^2$ pixel window fluctuations estimate reaches values almost three times higher than for the larger window sizes at the bottom edge of the field of view ($y = 0$), where the $F_O$ is lowest. At this point, the number of paired particle images found within smaller interrogation windows is too low to guarantee valid vectors with low uncertainty under the strong light-sheet misalignment conditions. Under these scenarios, the increased error induced by poor $F_O$ vastly outweighs the benefits of improved spatial resolution from smaller interrogation windows.

This example shows that knowledge about the light-sheet intensity profile and alignment help experimentalists to understand what exactly causes the loss-of-correlation and how the results could be improved. The alignment can be easily seen from a laser profiling camera, but is also indirectly assessable using the correlation-function volume ratio. Figure 7.23 shows that both methods result in a fairly good agreement over the broad range of the eight different laser sheet mismatch scenarios. The combination of both methods allows for easy alignment of the lasers prior to the experiment by using a profiling camera, and readjustments in the presence of a mean out-of-plane motion by means of the correlation-function volume ratio. The latter method also allows the detection of changes in $F_O$ due to fluctuations in the out-of-plane motion. This analysis not only confirms the simulation-based findings of the previous sections, but also substantiates the value and utility of the $F_O$ metric to characterise and improve the quality of a PIV measurement.
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from the wall and the out-of-plane motion of the particles is partly compensated by the offset between the light sheets is reduced due to motion $-0.03$, the valid vector detection $0.5$, as illustrated in Figure 7.23. If the resolution needs to be improved by reducing the interrogation window size, the light-sheet overlap must illustrate how the interrogation window size affects the estimation of the velocity fluctuations. While $2$ pixel $0$, the flow profiles deviate from the larger interrogation window estimates $2$ $0$ $0.2$ $0.4$ $0.6$ $0.8$ $1$ $0$ $0.2$ $0.4$ $0.6$ $0.8$ $1$

Figure 7.23: Estimated $F_O$ from PIV experiments based on the correlation/auto-correlation volume ratio compared with the estimation of $F_O$ from the light-sheet profiles according to equation 7.3

7.4 Chapter summary

The impacts of laser light sheet misalignment and width mismatch have been systematically investigated in this study via a set of synthetic PIV image simulations and laboratory experiments. From these results, the following key conclusions can be drawn:

- Results consistently demonstrate the rapid degradation in correlation quality which can occur when the two laser profiles used to capture a PIV image pair are no longer well matched, either in the width or alignment of their intensity profiles.

- The quantities and flow statistics of interest in an experiment can dictate the sensitivity of light sheet mismatch on experimental errors. Higher order flow statistics require greater levels of light sheet profile matching (greater $F_O$) to achieve low error results, compared with mean flow quantities, for example.

- The analysis from this study indicates that an $F_O > 0.8$ in an experimental setup should avoid the severe measurement errors associated with laser overlap. Particularly below the threshold $F_O < 0.65$, corresponding to a $1.35\sigma$ shift offset of two Gaussian light sheet profiles, rapid increases in spurious vectors and errors in flow statistics are consistently observed. Provided $F_O > 0.8$, we observe a negligible impact on the measurement of up to fourth-order flow statistics while
also providing an operational margin for robustness to dynamic, shot-to-shot laser instabilities.

- A PIV experiment involving various light sheet alignment and mismatch scenarios is outlined, and results are presented. Coupled with experiment-matched PIV simulations, these data confirm the significance of good laser overlap and the robustness of the laser mismatch simulation results.

- Laser profiling and the correlation/autocorrelation volume ratio both provide methods of estimating $F_O$. Laser profiling can isolate light sheet mismatch behaviours, while the volume ratio can additionally account for out-of-plane flow velocity components and fluctuations. Consistent $F_O$ estimates from both methods have been demonstrated using experimental data.

The overlap and matched intensity profile of PIV laser light sheets proves to be critical for the capture of quality data. However, laser analysis tools such as a laser profiling camera, as well as the correlation/autocorrelation volume ratio, can offer a clear, user friendly path towards improved PIV measurements.
Chapter 8

Linear approximation effects on PIV error in wall-bounded turbulent flows

Capturing additional data in any measurement can typically increase the accuracy and confidence in the experiment’s results by reducing random experimental and processing errors. Time-resolved measurements are a common means of capturing this extra information in PIV, although the fast camera capture rates and high energy pulsed lasers required for measurements in high Reynolds number air flows make continuous recording of PIV data extremely difficult and expensive. Performing sequential PIV image capture in short bursts of three or four images can offer a more practical and achievable path to increasing the data available in these kinds of high speed air measurements. Standard two-pulse PIV laser and camera equipment can be modified for use in this configuration – two dual-cavity laser systems with different polarisations can combine to provide the rapid four pulse laser burst, as well as two polarisation-filtered PIV camera systems for each captured field of view.

Given the effort required to capture this extra information in a high Reynolds number PIV measurement, it is important to consider how the data can be best exploited to reduce experimental errors. Depending on the measurement and processing configuration, increasing the number of sequential PIV images can average out random errors and processing artefacts, or alternatively establish a higher order estimate of the velocity field. However, the benefit of higher order velocity estimates can depend on the measured flow field, resolution and timescales considered in an experiment.

Conventional two pulse PIV inherently applies a linear approximation to all displacement estimates used in the calculation of the velocity field. Even if a correlation
algorithm could ‘perfectly’ process and spatially resolve the displacements from two pulse PIV image pairs, this linearity error would remain as a fundamental consequence of only two time points measured in sequence over a non-linear flow field. It is present irrespective of the measurement’s spatial resolution from the camera resolution/field of view and the interrogation window size. The duration between these two PIV images defines the temporal resolution of the measurement, and while a shorter interval offers greater temporal resolution, the measurement duration must also be long enough to provide sufficient particle pixel displacements to ensure good image cross-correlation.

Ideally, an experiment’s chosen measurement duration should resolve the smallest flow features of interest at the Kolmogorov scale, but practical considerations (such as necessary pixel displacements) often conflict with this objective. For example, PIV over a large field of view may be desirable, and this may be at the expense of not fully resolving all of the smallest flow scales due to limited imaging equipment. Such a scenario is common in the University of Melbourne fluids laboratory, where studies simultaneously examining a range of large and small flow scales are frequently of interest (de Silva et al., 2014, Squire et al., 2016, and others). Faced with this dilemma, the linear approximation error can be reduced in one of three ways:

1. Apply a post-measurement correction to the vector field to compensate for bias due to curved streamlines, such as the method proposed by Scharnowski and Kähler (2013).

2. Increase the camera resolution in the experiment, such that the same particle pixel displacement can be achieved over a smaller measurement duration (although in many carefully conceived experiments, this may often be considered impractical).

3. Introduce additional laser pulses to extract further data in between the existing measurement times, thereby improving the temporal resolution. This may be at the expense of reducing the time interval between successive laser pulses, but PIV data also remains over the original measurement interval, which can be additionally exploited by sophisticated cross-correlation algorithms. Additional cameras, or the introduction of double-exposed imaging can be used to capture the increased number of laser pulses.

The third option presented here offers a less conventional alternative to addressing temporal resolution, although its value is dependent on the significance of linear approximation errors in typical PIV experiments. So what relative impact does this linearity assumption have on the measurement of turbulent wall-bounded flows, and
to what extent would three or four pulse PIV measurements reduce these errors? This chapter investigates the accuracy with which linear and higher order displacement estimates can resolve the motions observed in turbulent wall-bounded flows over typical measurement timescales.

8.1 Methodology

The errors associated with various order estimates of velocity are determined for the streamwise/wall-normal plane of an \( \text{Re}_\tau \approx 1000 \) time-resolved channel flow DNS dataset, from the Johns Hopkins Turbulence Database (Graham et al., 2016). This particular plane is commonly examined in PIV wall-bounded turbulence measurements, and exhibits a progression of flow trajectory characteristics and velocities, from the zero velocity at the wall (due to the no-slip condition) to the bulk flow at the centre of the channel. Details of the DNS domain applied in this simulation, as well as other parameters in this analysis are summarised in table 8.1.

Table 8.1: Linearity DNS and analysis parameters

<table>
<thead>
<tr>
<th>DNS Parameters</th>
<th>999.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streamwise dimension ((x^+))</td>
<td>1226(^+) (100 cells)</td>
</tr>
<tr>
<td>Spanwise dimension ((y^+))</td>
<td>31(^+) (5 cells)</td>
</tr>
<tr>
<td>Wall-normal dimension ((z^+))</td>
<td>999(^+) (256 cells)</td>
</tr>
<tr>
<td>Total time duration ((t^+))</td>
<td>10.0625(^+) (605 steps)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tracer locations</td>
</tr>
<tr>
<td>Studied timescales ((\Delta T^+))</td>
</tr>
<tr>
<td>Studied timescale increment</td>
</tr>
</tbody>
</table>

The linearity characteristics of the DNS velocity fields are studied directly (via particle advection rather than via a simulated PIV experiment) to isolate the typical displacement characteristics of the flow field, thereby excluding potential errors associated with PIV image and correlation processing from this analysis. The finely-incremented stepwise displacement of 500,000 random starting locations (or virtual tracer particles) distributed throughout the DNS field are considered over the simulated time domain. Displacements coinciding with PIV measurement time intervals are extracted from the time-history, and a best-fit is applied (see figure 8.1). Differentiating the best-fit function and solving for the value at the mid-point of the PIV sequence yields the velocity estimate.
This estimate is compared with the actual DNS velocity at the mid-point of the PIV sequence (from the same starting location), resulting in the relative error ($\epsilon$) associated with this process:

$$
\epsilon_u = \left| \frac{u_{\text{DNS}} - u_{\text{estimate}}}{u_{\text{DNS}}} \right| \times 100
$$

(8.1)

Error results are binned according to the wall-normal height of every mid-sequence location. This procedure is repeated for each of the 500,000 displacement starting locations, for a variety of different PIV interval configurations and orders of the best-fit function.

Various simulated measurement durations are modelled to cover a wide range of possible experiment and flow study scenarios, where the duration is defined using the viscous timescale, $\Delta T^+$:

$$
\Delta T^+ = \frac{tU_{\tau}^2}{\nu}
$$

(8.2)

The time duration, $t$, is measured in seconds, $U_{\tau}$ is the friction velocity and $\nu$ is the kinematic viscosity of the fluid. Typically, the measurement duration applied in an experiment is dictated by the timescales of the small flow features of interest (such as the Kolmogorov scale, for example), balanced with practical considerations, such as ensuring sufficient particle pixel displacement for good correlation quality.
In this analysis, $\Delta T^+$ spans the interval from the first to the last laser pulse (ie: $\Delta T = t_{\text{last pulse}} - t_{\text{first pulse}}$). Therefore any additional laser pulses added to the PIV measurement configuration are inserted in-between the fixed start and end laser pulses, leaving the total measurement interval unchanged. While this configuration does alter the time interval between successive laser pulses, it permits any benefits of multipulse PIV in addressing linear approximation effects to be fully captured – even under some extreme scenarios where the Nyquist-Shannon sampling criterion may not be satisfied with two pulse PIV, but is satisfied when using this multipulse timing configuration. The laser pulse timing sequence of the uniformly spaced two, three and four pulse PIV configurations considered in this analysis are illustrated in figure 8.2. An alternate timing configuration is also later discussed in Chapter 9, where additional laser pulses add to the length of the total measurement interval.

8.2 Discussion of results

Errors due to the linearity approximation of a wall-bounded flow are determined by the turbulence of the local flow field. Consequently this error can vary with distance from the wall, $z^+$, as shown in figure 8.3 by the two pulse linearity mean error magnitude over a $\Delta T^+ = 1$ timescale, binned at various wall-normal locations. Error trends consistent with these results are also observed in both three and four pulse PIV configurations. Note that viscous units (rather than percentage errors) are used in figure 8.3 to compare the streamwise and wall-normal velocity errors. Given similar error behaviour from both velocity components, the streamwise percentage error, calculated using equation 8.1, will be applied in the remainder of the analysis.
The greatest linearity errors are observed close to the wall due to elevated near-wall turbulence, and consequently a near-wall location (at a \( z^+ \approx 2 \)) will also be used in subsequent error plots to assess the worst-case linearity scenario.

PIV experiments are, however, typically performed over different measurement time intervals, dictated by the measurement plane, flow velocity, camera resolution and field of view, in order to achieve sufficient pixel displacements across PIV images while minimising out-of-plane loss-of-pairs. Therefore considering how measurement intervals can impact the linearity error associated with different PIV configurations can also help to determine an experiment’s optimal parameters and achievable accuracy.

### 8.2.1 Uniform interval spacing

At a given wall-normal height, the distribution of displacement errors for a specified measurement interval can be illustrated with a probability density function. Figure 8.4 shows the spread of streamwise velocity errors for two pulse measurements observed at a wall-normal location of \( z^+ \approx 2 \), over \( \Delta T^+ = 1 \) and \( \Delta T^+ = 2 \) intervals. By repeating this procedure over a range of measurement intervals \( (\Delta T^+) \), a contour plot of the error probability density functions can be compiled for a given wall-normal height. Figure 8.5 shows the resulting streamwise error contour plots for two pulse, three pulse, and four pulse measurements with uniform interval spacing. Colour contours indicate the p.d.f. values, while the white lines show the mean error magnitude resulting from each measurement interval. The smallest errors are observed over short time intervals.
Chapter 8. Linear approximation effects on PIV error

Figure 8.4: Streamwise velocity error magnitude probability density function of two pulse measurements with uniform interval spacing at $z^+ \sim 2$, over $\Delta T^+ = 1$ and $\Delta T^+ = 2$ intervals.

Figure 8.5: Compiled streamwise velocity error magnitude probability density functions for two, three and four pulse configurations at $z^+ \sim 2$. The white lines indicate the mean streamwise error magnitude.
Figure 8.6: Streamwise linearity mean error with uniform interval spacing over different PIV measurement durations at $z^+ \sim 2$

where lower-order approximations remain representative of a flow tracer’s trajectory. However, a rapid increase in the spread of velocity errors is observed in most cases for $\Delta T^+ > 1$. Similar error behaviour is observed between two pulse, three pulse quadratic and four pulse quadratic fit cases, while under these idealised, noise-free simulation conditions, the four pulse cubic fit scenario offers increased robustness to linearity errors.

Although the error distribution characteristics shown by the p.d.f. contours in figure 8.5 are important in assessing linearity behaviour, the mean error magnitude (the white lines in figure 8.5) also closely reflects these trends, and enable direct comparison of the test cases. These mean error magnitude quantities will therefore be used to inform the comparative discussion of linearity errors and performance. Figure 8.6 shows a comparison of the relative streamwise mean error over a range of measurement durations and uniformly spaced PIV configurations. All PIV configurations exhibit increasing linearity error as the $\Delta T^+$ measurement interval increases. The four pulse configuration with a quadratic best-fit achieves modest reductions in the linearity error, compared with two and three pulse configurations. Meanwhile, the cubic best-fit arrangement yields significant linearity error reductions thanks to the additional higher order term used by the best fit to approximate the fluid trajectory. However the three pulse quadratic and four pulse cubic best-fits are considered an “exact fit”,

![Diagram](image-url)
where the number of data points (constraints) equals the number of unknowns in the polynomial fit equation. Consequently, the fit function is forced to pass through every displacement point, making the function and midpoint gradient extremely susceptible to experimental noise and errors in displacement measurements. A lower order best-fit, such as the four pulse quadratic configuration, is an overdetermined system, with more data points or constraints than there are unknowns in the best-fit function. A least-squares best-fit function must therefore be determined to approximate a solution, which applies some smoothing to the displacement trajectory, and may offer increased robustness to the noisy data commonly encountered in experiments (illustrated in figure 8.7). Furthermore, under ‘perfect’ conditions without noise or errors in displacement measurements, three pulse PIV with linear (not shown here) or quadratic best-fits yield the same velocity result at the mid-point of the measurement interval as a two pulse configuration. Additional measurement error is not considered in this investigation, although linear-fit three pulse and quadratic-fit four pulse measurements would be expected to offer increased robustness to noise and errors.

The results in figure 8.6 can be further verified by considering a simplified mathematical approximation of two pulse linear effects on a fluid trajectory. Using a sine wave to approximate a turbulent flow trajectory with a varying curvature, two sample points of the wave are considered over a range of time intervals. The linear fit function of the two sample configuration can then be determined, as well as the associated velocity estimate at the midpoint of the interval (equation 8.3).
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\[ u_{\text{mid}, \text{est}} = \frac{\sin(2\pi at_2) - \sin(2\pi at_1)}{t_2 - t_1} \]  

(8.3)

This estimate can then be compared with the actual midpoint velocity of the trajectory (equation 8.4) to find the percentage error (using equation 8.1). The resulting expression is shown in equation 8.5, and is plotted as a grey line against the DNS results in figure 8.6. To align this function with the DNS data in figure 8.6, the wavelength of the sinusoid was adjusted to \( \Delta T^+ = 36 \) (ie: set \( a = \frac{1}{36} \) in equations 8.3, 8.4 and 8.5).

\[ u_{\text{mid, sine}} = 2\pi a \cos \left( 2\pi a \left( \frac{t_2 - t_1}{2} + t_1 \right) \right) \]  

(8.4)

\[ \epsilon_{2 \text{ pulse theory}} = 1 - \left| \frac{\sin(2\pi at_2) - \sin(2\pi at_1)}{2\pi a(t_2 - t_1)\cos(\pi a(t_1 + t_2))} \right| \times 100 \]  

(8.5)

This highly simplified mathematical formulation closely follows the trend of the 2 pulse DNS data for \( \Delta T^+ < 1.5 \), before diverging to greater error values. Due to the multi-scale nature of turbulence, this observed divergence is to be expected from a single frequency sinusoidal approximation of displacement trajectories.

### 8.2.2 Nonuniform interval spacing

Nonuniform spacing of the laser pulses in four pulse PIV measurements may enable further reduction in the linearity error. To investigate this behaviour, a variety of nonuniform intervals were tested on a four pulse quadratic best-fit configuration, summarised in table 8.2. Only symmetrical nonuniform intervals are considered, to ensure unbiased treatment of start and end effects.

<table>
<thead>
<tr>
<th>Interval Test Case</th>
<th>Proportion of ( \Delta T^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta t_{4,1}^+ )</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>0.05</td>
</tr>
</tbody>
</table>
The streamwise linearity error difference using the five test case intervals, which compares the errors from uniform and nonuniform spacing of the four laser pulses, is shown in figure 8.8 over a range of total measurement $\Delta T^+$ durations. In this comparison, a positive error difference indicates that the error from nonuniform interval spacing is lower than that observed with uniform pulse spacing. In most interval cases, superior nonuniform interval error performance is observed over longer measurement intervals, and particularly in the near-wall region. However, any streamwise error performance changes due to nonuniform intervals are relatively minor compared with total mean error effects (which are an order of magnitude greater, see figure 8.6). Furthermore, not all nonuniform pulse intervals offer improvements in error – the short delays between pulses 1-2 and pulses 3-4 in test cases 4 and 5 result in higher errors than with uniform pulse spacing. Test case 2 (using 0.20/0.60/0.20 intervals) provides the lowest error performance of these configurations for timescales $\Delta T^+ < 5$ in the tested channel flow. This optimal nonuniform pulse spacing is used in all subsequent
Figure 8.9: Streamwise linearity mean error with nonuniform interval spacing over different PIV measurement durations at $z^+ \sim 2$

Figure 8.9 compares the streamwise linearity error of the optimal nonuniform interval with the uniformly spaced two and four pulse PIV configurations. Clearly only modest improvements can be gained using nonuniform spacing in quadratic-fit four pulse PIV measurements. Depending on the control of error sources in an experiment, measurement and processing errors may exert greater influence on the accuracy of results.

8.2.3 Comparison with published experiment parameters

To offer some context to the impact of errors associated with the linear assumption in two pulse PIV measurements, the effect of these errors on a selection of published PIV measurements over a streamwise-wall normal plane are considered. Negligible differences are assumed between the non-linear characteristics of the turbulent boundary layer flows considered in many of these experiments, and the DNS channel flow used in this analysis. Table 8.3 summarises the key parameters of the published PIV datasets, including the crucial calculation of each experiment’s $\Delta T^+$ flow timescale. The corresponding estimate of streamwise linearity errors covering timescales $\Delta T^+ = [0, 2.5]$ are shown in figure 8.10, where grey bars have been overlaid at documented experiment timescales. The corresponding two pulse streamwise linearity error estimates
Table 8.3: Linearity error of published PIV experiments

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Wall Type</th>
<th>$U_\infty$ (m/s)</th>
<th>$Re_\tau$</th>
<th>$\Delta t$ (µs)</th>
<th>$u_\tau$ (m/s)</th>
<th>$\nu \times 10^{-5}$</th>
<th>$\Delta T^+$</th>
<th>2 Pulse</th>
<th>4 Pulse Quad.</th>
<th>4 Pulse Cubic</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFOV High Mag (de Silva et al., 2014) Smooth</td>
<td>10</td>
<td>7,870</td>
<td>15</td>
<td>0.33</td>
<td>1.541</td>
<td>0.11</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>&lt;0.004</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>14,500</td>
<td>7</td>
<td>0.63</td>
<td>1.534</td>
<td>0.18</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>&lt;0.004</td>
<td></td>
</tr>
<tr>
<td>LFOV High Mag (de Silva et al., 2014) Smooth</td>
<td>30</td>
<td>19,500</td>
<td>5</td>
<td>0.94</td>
<td>1.630</td>
<td>0.27</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>&lt;0.004</td>
<td></td>
</tr>
<tr>
<td>LFOV (de Silva et al., 2014) Smooth</td>
<td>10</td>
<td>7,870</td>
<td>70</td>
<td>0.33</td>
<td>1.541</td>
<td>0.51</td>
<td>0.05</td>
<td>0.04</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>LFOV (de Silva et al., 2014) Smooth</td>
<td>20</td>
<td>14,500</td>
<td>35</td>
<td>0.63</td>
<td>1.534</td>
<td>0.91</td>
<td>0.15</td>
<td>0.13</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>LFOV (de Silva et al., 2014) Smooth</td>
<td>30</td>
<td>19,500</td>
<td>23</td>
<td>0.94</td>
<td>1.630</td>
<td>1.23</td>
<td>0.29</td>
<td>0.24</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>LFOV (Squire et al., 2016) Rough</td>
<td>12.3</td>
<td>11,600</td>
<td>75</td>
<td>0.49</td>
<td>1.550</td>
<td>1.16</td>
<td>0.29</td>
<td>0.24</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>LFOV (Squire et al., 2016) Rough</td>
<td>10.3</td>
<td>6,560</td>
<td>25</td>
<td>0.34</td>
<td>1.516</td>
<td>0.19</td>
<td>0.67</td>
<td>0.58</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>Tower (Squire et al., 2016) Smooth</td>
<td>20.5</td>
<td>12,310</td>
<td>12</td>
<td>0.65</td>
<td>1.525</td>
<td>0.33</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>&lt;0.004</td>
<td></td>
</tr>
<tr>
<td>Tower (Squire et al., 2016) Smooth</td>
<td>29.6</td>
<td>16,940</td>
<td>6</td>
<td>0.91</td>
<td>1.500</td>
<td>0.33</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>&lt;0.004</td>
<td></td>
</tr>
<tr>
<td>Tower (Squire et al., 2016) Rough</td>
<td>12.4</td>
<td>12,140</td>
<td>22</td>
<td>0.49</td>
<td>1.509</td>
<td>0.35</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>&lt;0.004</td>
<td></td>
</tr>
<tr>
<td>Tower (Squire et al., 2016) Rough</td>
<td>20.4</td>
<td>18,460</td>
<td>14</td>
<td>0.82</td>
<td>1.550</td>
<td>0.61</td>
<td>0.07</td>
<td>0.06</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>GFOV (de Silva et al., 2015) Smooth</td>
<td>10</td>
<td>2,650</td>
<td>70</td>
<td>0.37</td>
<td>1.543</td>
<td>0.61</td>
<td>0.07</td>
<td>0.06</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>GFOV (de Silva et al., 2015) Smooth</td>
<td>20</td>
<td>5,100</td>
<td>35</td>
<td>0.70</td>
<td>1.529</td>
<td>1.11</td>
<td>0.24</td>
<td>0.20</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>GFOV (de Silva et al., 2015) Smooth</td>
<td>30</td>
<td>7,250</td>
<td>23</td>
<td>1.02</td>
<td>1.532</td>
<td>1.57</td>
<td>0.48</td>
<td>0.41</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>Towed Plate (Start) (Lee et al., 2014) Smooth</td>
<td>1.0</td>
<td>494</td>
<td>1000</td>
<td>0.045</td>
<td>0.091</td>
<td>2.22</td>
<td>0.79</td>
<td>0.66</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>Towed Plate (End) (Lee et al., 2014) Smooth</td>
<td>1.0</td>
<td>2,550</td>
<td>1000</td>
<td>0.037</td>
<td>0.094</td>
<td>1.45</td>
<td>0.45</td>
<td>0.37</td>
<td>0.018</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 8. Linear approximation effects on PIV error

Figure 8.10: Streamwise linearity mean error estimates for experiments over $\Delta T^+ = [0, 2.5]$ at $z^+ \sim 2$

associated with each experiment are also listed in table 8.3, alongside the estimated errors if four pulse PIV techniques were used.

These results indicate that even using a two pulse measurement configuration produces a relative streamwise linearity error of $< 0.8\%$. This error magnitude further decreases at higher (and in PIV, more common) wall-normal measurement heights. An error of this magnitude can be easily eclipsed by other experimental errors, such as shot-to-shot laser jitter and light sheet mismatch, documented in Chapters 6 and 7. Under ideal, no noise conditions, a four pulse cubic best-fit configuration offers some advantages (although small in real terms), and negligible gains can be achieved with the use of a four pulse quadratic best-fit configuration with nonuniform interval spacing. However, the four pulse quadratic best-fit configuration may present advantages under real-world, noisy experiment conditions.

8.3 Chapter summary

This investigation has considered the impact of the linearity assumption inherent in two pulse PIV measurements of turbulent wall-bounded flows. The potential advantages of using three or four pulse PIV configurations on linearity error have been studied, producing the following important results:
• Under ideal conditions, the magnitude of linearity error at common measurements timescales is quite small (< 0.8% of the streamwise velocity), particularly when compared with the magnitude of other typical experimental errors.

• Four pulse PIV measurements can offer reductions in the linearity error of the measurement, with modest gains under ideal conditions using a quadratic best-fit and greater benefits with the use of a cubic best-fit. However, under the noise levels common in experimental conditions, a quadratic best-fit is expected to provide more robust performance.
Chapter 9

Multipulse PIV processing techniques and comparison

The sequential capture of multiple PIV images, as introduced in Chapter 8, can exploit additional PIV data to reduce measurement error – in particular decreasing the random errors introduced during image processing and cross-correlation. The possible benefits of the multipulse technique are investigated in this study by comparing the performance of four pulse PIV measurements with standard two pulse PIV. However, the introduction of additional laser pulses into the PIV capture sequence can also increase the complexity of the experimental setup, as well as the measurement’s sensitivity to experimental errors. For example, a multipulse PIV experiment may require the use of extra laser and camera systems, which can complicate the refinement of laser alignment and light sheet matching, since four laser beams must be aligned, rather than just two (discussed in Chapters 6 and 7). So what are the potential benefits of a multipulse PIV configuration and are these advantages sufficient to outweigh the practical complications and experimental errors involved in setting up this more complex measurement? This chapter compares the accuracy of multipulse PIV measurements with results from standard two pulse PIV using three different correlation approaches, and considers the robustness of each measurement’s accuracy to experimental errors (such as laser misalignments).

9.1 Multipulse PIV algorithms

Three distinct PIV correlation algorithms are considered in this investigation of multipulse PIV performance. The simplest processing of multipulse data is based upon the ensemble correlation algorithm, first outlined by Meinhart et al. (2000),
which averages together the correlation results of adjacent PIV image pairs. The implementation of a pyramid correlation-like scheme (based on the work of Sciacchitano et al., 2012) is a more sophisticated extension of the ensemble correlation method, which also includes other temporal combinations of the PIV image sequence in the averaged result. By the direct averaging of correlation results, both of these methods assume generally linear flow behaviour. A correlation procedure based around the fluid trajectory correlation (Lynch and Scarano, 2013), however, uses the additional information from a multipulse measurement to perform a best-fit to interrogation window displacements, which can determine a higher order velocity estimate of the flow. This assumes either the presence of non-linear flow behaviours, or that experimental noise is impacting the accuracy of the measurement and requires greater low-pass filtering. Further details regarding the procedures and implementation of these algorithms are presented later in this section.

These algorithms are generally designed for, and applied to, time-resolved PIV measurements (typically of lower speed flows), where a long or continuous sequence of PIV images are available. Due to the relatively high Reynolds number flows of interest in this study, our investigations are limited to the processing of four pulse PIV burst sequences, a somewhat shorter image sequence than commonly studied using these algorithms. In this constrained scenario, the relative performance of these correlation techniques are, to-date, not well documented. This study aims to address this knowledge gap, particularly for the application of four pulse burst PIV measurements to wall-bounded flows.

9.1.1 Ensemble correlation

The ensemble correlation approach, detailed by Meinhart et al. (2000), has remained one common way of utilising additional PIV images in a sequence to improve the signal-to-noise ratio of the measurement, and thereby reduce error. In this technique, contiguous PIV image pairs are cross-correlated, as with standard two pulse processing. Multiple cross-correlation surfaces are thereby generated, and each instantaneous cross-correlation surface \( R_{ij} \), which describes the cross-correlation function of images \( i \) and \( j \), is then averaged together to produce a single average cross-correlation function:

\[
\frac{R_{12} + R_{23} + R_{34}}{3} = R_{\text{ens}}
\]

This procedure dampens the noise floor of the correlation, since random noise peaks are unlikely to be co-located in multiple cross-correlations, while also amplifying
the common displacement peak. Figure 9.1 illustrates this noise dampening, where the colour axis has been restricted to emphasise the changes in the noise floor characteristics. The sub-pixel location of the displacement peak is then located on the average cross-correlation surface in the conventional way.

Combining the results from multiple PIV images with this technique can reduce the prevalence of spurious vectors and the magnitude of measurement error, but the method assumes zero acceleration of the flow (constant velocity, or linear flow behaviour) over the sampling period. Velocity changes in-between the measured PIV image pairs will result in variations to the correlation peak location of each instantaneous cross-correlation, such that all of the instantaneous correlation peak displacements may no longer coincide and be amplified correctly during the averaging process. The utility of this technique can therefore be dependent on the behaviour of the measured flow field, the Reynolds number, and the timescales of interest.

### 9.1.2 Pyramid correlation

The pyramid correlation (Sciacchitano et al., 2012) is a more comprehensive implementation of the cross-correlation averaging principle introduced by the ensemble correlation method. This technique not only averages together the instantaneous cross-correlation of contiguous PIV image pairs (pairing of images 1-2, 2-3, and 3-4), but also other possible non-contiguous PIV image pair combinations that can be made over differing time intervals (pairing of images 1-3, 2-4, and 1-4). Applying two-image cross-correlation to every possible image pair combination of a four image
burst, for example, produces a ‘pyramid’ of instantaneous correlations over a range of measurement intervals (see figure 9.2). Due to differing measurement intervals for these image pairings, corrections to adjust for differing pixel displacements and correlation displacement peak locations are necessary. Rescaling the instantaneous cross-correlation functions onto the longest measured interval aligns the correlation peaks using a homothetic transformation, or dilation operation. This procedure is given in equation 9.2 and shown graphically in figure 9.3, where the red boxes illustrate the extent of the rescaled and interpolated cross-correlation domain.
\[ R_{n}^{\Delta t_{n_{h}}} (\Delta x) = R_{n} \left( \frac{n}{n_{h}} \Delta x \right) \]  \hspace{1cm} (9.2)

This procedure also broadens the correlation peaks measured over shorter time intervals to improve robustness, while correlations over longer time intervals provide the sharp correlation peak needed to determine the sub-pixel displacement. The resulting correlation functions are summed together, and the correlation magnitude is divided by \( n_{h} \), as shown in equation 9.3.

\[ R_{\text{pyr}}^{\Delta t_{n_{h}}} (\Delta x) = \frac{1}{n_{h}} \sum_{n=1}^{n_{h}} R_{n}^{\Delta t_{n_{h}}} (\Delta x) \]  \hspace{1cm} (9.3)

The average cross-correlation displacement peak is then located and processed conventionally. Criteria can be applied during this procedure to restrict the local height of the correlation pyramid, \( n_{h} \), considered in calculations based on flow and measurement characteristics. Limiting \( n_{h} \) below the maximum pyramid height can exclude correlations spanning longer time intervals (\( R_{14} \), for example, which may produce greater errors) under certain scenarios, to prevent corruption of the averaged pyramid result. For example, a signal-to-noise ratio criteria can limit the local height, \( n_{h} \), to maintain a signal-to-noise ratio > 1.5. Note that a correlation pyramid height of \( n_{h} = 1 \) considers the same correlation functions as in the ensemble correlation algorithm. An adapted form of the pyramid algorithm is applied to the in-house MATLAB code used in this study.

A greater amount of information (for correlation noise reduction in particular) can be extracted from a finite set of PIV images using the pyramid correlation, when compared with the ensemble correlation method (when \( n_{h} > 1 \)). In a four pulse PIV burst, for example, the pyramid correlation can benefit from averaging up to six instantaneous cross-correlation functions, compared with averaging just three cross-correlation functions with the ensemble correlation method. However, the same assumption of constant velocity flow applies to this technique, as with ensemble correlation. Therefore, the measurement timescales, Reynolds number, and flow field must be considered when applying this algorithm to PIV data.

### 9.1.3 Fluid trajectory correlation

The fluid trajectory correlation (FTC) enables higher order estimates of fluid motions to be captured and analysed by tracking interrogation window patterns (Lynch and Scarano, 2013). A simplified implementation of FTC is applied to the in-house
MATLAB code used in this analysis. Standard two pulse cross-correlation is first performed on contiguous PIV image pairs (pairing images 1-2, 2-3, and 3-4), and interpolation between the resulting velocity vectors allow stepwise displacement estimates to be back-calculated from small velocity increments (Moore et al., 2011). This displacement estimate establishes a prediction of each interrogation window’s trajectory over the total measurement duration. Cross-correlation of image pairs about the central measurement point (akin to a central differencing-type arrangement, using 1-2, 2-3 and 2-4 image pairings in this case) are subsequently performed to correct errors from the predicted displacement trajectory. Multiple correlation passes can be processed, as with other PIV algorithms. A least-squares fit of the final output displacement trajectory is calculated using the desired polynomial order fit (see figure 9.4), from which the velocity or higher order quantities (acceleration, for example) can be found at the mid-point of the measurement interval.

This technique enables non-linear flow behaviours to be properly analysed, as well as the calculation of higher order flow measures. While this allows longer measurement durations to be captured, involving greater non-linear flow characteristics, the results from Chapter 8 suggest that linearity errors may not be significant over the timescales considered in this analysis (which also cover the common timescales applied to typical wall-bounded PIV measurements). However, random errors can be reduced from the low-pass filtering effects of the least-squares best fit operation.
9.1.4 Other methods

The three multipulse algorithms outlined in detail here (and summarised schematically in figure 9.5) constitute a variety of approaches to dealing with additional PIV data. While other alternative algorithms for processing multipulse PIV data exist in literature, they remain beyond the scope of this analysis. One notable example is where multipulse PIV data is used to allow the dynamic post-measurement selection of optimal two pulse image pair separation, depending on local flow characteristics and the signal-to-noise ratio of the correlations. For example, images 1 and 4 may be correlated in some regions, while image pairs 1-3 or 1-2 may be applied elsewhere in the field of view. Assessments of this approach have been outlined by Hain and Kähler (2007), and Persoons and O’Donovan (2010), but may be considered by some to be superseded by more recent FTC and pyramid correlation algorithms.

Recent attention on advanced particle tracking velocimetry techniques may also offer applications to constrained four-pulse burst measurement scenarios. In particular, continuing development of the Shake-The-Box technique may provide some interesting future opportunities for the multipulse experiments discussed in this chapter, as well as the possibility of a shift from image velocimetry to tracking velocimetry (Novara et al., 2016, Fuchs et al., 2017).
9.2 Algorithm performance in PIV simulations

Synthetic image PIV simulations are used to systematically assess the performance of the tested PIV algorithms on multipulse data, using the in-house software package outlined in Chapter 3. This enables multiple PIV configurations to be tested efficiently, without time-consuming changes to a laboratory configuration. Once a better understanding of key performance variables is obtained from these simulations, the practicality of a multipulse laboratory experiment can be assessed, as well as determining an optimal measurement configuration.

9.2.1 Methodology

This study is restricted to the comparison of a four pulse PIV image sequence with standard two pulse PIV image pairs, an achievable configuration with the current equipment available at the University of Melbourne for use in a laboratory multipulse PIV measurement.

Table 9.1: Summary of multipulse simulation parameters

<table>
<thead>
<tr>
<th>Measurement plane</th>
<th>Streamwise × Wall-Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re_{\tau}$</td>
<td>999.35</td>
</tr>
<tr>
<td>DNS domain ($x^+ \times z^+$)</td>
<td>1496 × 997</td>
</tr>
<tr>
<td>DNS time step ($t^+$)</td>
<td>0.065</td>
</tr>
<tr>
<td>DNS database time step ($t^+$)</td>
<td>0.32</td>
</tr>
<tr>
<td>Image bit-depth</td>
<td>16 bit</td>
</tr>
<tr>
<td>Gaussian light sheet thickness ($y^+$)</td>
<td>$\sigma = 1.7^+$</td>
</tr>
<tr>
<td>Studied timescales ($\Delta T^+$)</td>
<td>0.4$^+$ to 2.5$^+$</td>
</tr>
<tr>
<td>Studied timescale interval</td>
<td>0.1$^+$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Image resolution (viscous units/pixel)</th>
<th>1.5</th>
<th>1.0</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image size (pixels)</td>
<td>997 × 665</td>
<td>1496 × 998</td>
<td>2244 × 1496</td>
</tr>
<tr>
<td>Final window size (pixels)</td>
<td>32 × 32</td>
<td>32 × 32</td>
<td>32 × 32</td>
</tr>
<tr>
<td>Final window size ($x^+ \times z^+$)</td>
<td>48 × 48</td>
<td>32 × 32</td>
<td>16 × 16</td>
</tr>
</tbody>
</table>

A turbulent channel flow DNS data set from the Johns Hopkins Turbulence Database (Graham et al., 2016) at $Re_{\tau} = 999$ is used in this analysis (the same data set as used in Chapter 8), thanks to the finely time-resolved data available. Planar PIV simulations were performed on the half-channel over a streamwise-wall normal plane, and results are averaged over ten distinct DNS flow fields. Further details of the simulation configuration are outlined in Table 9.1. A Gaussian light sheet profile is applied to all simulations, with a standard deviation of $\sigma = 1.7$ viscous units. An infinite depth of field is used in synthetic images throughout the study. All correlation
algorithms use a three pass configuration, starting with an interrogation window size of $64 \times 64$ pixels, and a final interrogation window size of $32 \times 32$ pixels.

Two crucial measurement variables are examined in greater detail throughout this multipulse performance analysis – the PIV measurement timescale of the flow, which can dictate the non-linearity of the observed flow behaviour, and the resolution of the imaging system, which can alter the impact of in-plane flow gradients on interrogation windows. This study will therefore examine algorithm performance over a range of measurement timescales, from a $\Delta T^+$ of $[0.4, 2.5]$, and three common imaging resolutions, corresponding to 0.5 viscous unit/pixel, 1.0 viscous unit/pixel, and 1.5 viscous units/pixel. As in Chapter 8, the total measurement timescale $\Delta T^+$ spans the interval from the first to the last laser pulse (see figure 9.6). Unless otherwise stated, additional laser pulses in the four pulse configuration are inserted between the fixed start and end pulses, a configuration that was chosen to keep the total measurement interval unchanged. Therefore, the 2 pulse laser interval is equal to total measurement timescale, ie: $\Delta T^+ = \Delta t^+_{2,1}$, while under the four pulse configuration, $\Delta T^+ = \Delta t^+_{4,1} + \Delta t^+_{4,2} + \Delta t^+_{4,3}$. The corresponding image and interrogation window parameters are also detailed in table 9.1. Particle image diameters are held constant in pixels and the number of simulated particles is scaled for constant particle image density.

The performance of the multipulse PIV algorithms is compared under idealised conditions, involving uniform particle sizes, no image noise, and identical light sheet profiles (perfect light sheet matching, ie: $F_O = 1$).
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9.2.2 Distribution of simulation errors

Each simulation for a given correlation algorithm, measurement time interval, and image resolution produces an output velocity field, and the normalised median test is used to detect and omit any spurious vectors (Westerweel and Scarano, 2005). Identical, recommended median test values are used for all simulation cases. Following outlier detection, the velocity field can be compared with corresponding DNS velocities to calculate the magnitude of the measurement error. The DNS velocity fields used for comparison are taken from the mid-point of the measurement time interval, and have been spatially filtered in the streamwise and wall-normal directions to correspond with the final interrogation window size of the measurement. Figure 9.7 shows a sample streamwise velocity error field resulting from this procedure, which corresponds to a 0.5 viscous unit/pixel two pulse PIV simulation at $\Delta T^+ = 1.0$. Vectors which have been detected as spurious are shown as white cells.

Greater streamwise velocity errors are observed close to the channel wall, caused by the increased turbulence intensity of small scale near-wall turbulence (which may not be fully resolved by the measurement), as well as by lower velocities and associated particle pixel displacements. This trend is reinforced by figure 9.8, which shows the average streamwise velocity error with wall-normal height for 0.5 viscous unit/pixel resolution two pulse PIV simulations at $\Delta T^+ = 1.0$, averaged over the ten DNS flow fields used in this analysis. Greatest velocity errors are found for $z^+ < 100$, which approaches a maximum error of 7.3%, while the dotted line indicates the 1.7% average streamwise velocity error across the examined channel domain. The cumulative impact of errors covering the entire simulation domain is considered in this investigation,
Figure 9.8: Streamwise velocity error with wall-normal height for two pulse PIV simulations with a 0.5 viscous unit/pixel resolution at $\Delta T^+ = 1.0$, averaged over ten DNS flow fields. The dotted black line indicates the average streamwise velocity error over the examined channel domain.

Figure 9.9: Streamwise velocity error probability density function (p.d.f.) for a two pulse PIV simulation with a 0.5 viscous unit/pixel resolution at $\Delta T^+ = 1.0$.

with a subsequent emphasis on the mean error value. Therefore, any measurements isolating the near-wall region of a flow will encounter higher streamwise velocity errors than the mean error values documented in this study (figure 9.8 may provide a useful reference in this regard).

A probability density function (p.d.f.) of the streamwise velocity error from the field in figure 9.7 can be determined to study the spread of error values in the domain, as shown in figure 9.9. This calculation of the streamwise error probability density function is repeated for each measurement time interval simulation, and compiled...
Figure 9.10: 1.5 viscous unit/pixel resolution streamwise velocity error contours of probability density function over different timescales ($\Delta T^+$), using two pulse and four pulse PIV algorithms. The red line shows the mean streamwise error as vertical slices to produce contour plots. The resulting streamwise velocity error contour plots for 1.5, 1.0 and 0.5 viscous unit/pixel resolution simulations are shown in figures 9.10, 9.11, and 9.12, respectively. Each contour plot considers a single correlation algorithm and image resolution, displaying streamwise error trends across different measurement timescales. The superimposed red lines also indicate the mean streamwise error for each error distribution.

While the mean errors are generally consistent with the behaviour of the p.d.f. error contours, some simulation cases (such as using standard 2 pulse PIV processing, particularly in the 1.5 and 1.0 viscous unit/pixel cases) show deviations between these parameters. The observed variations are symptomatic of an increasing frequency of large errors (undetected spurious vectors), which can bias the mean error value. The normalised median test parameters were held constant in these simulations, for consistency between all test cases, but the median test could be more effective at longer timescales by tuning the parameters for improved spurious vector detection sensitivity.

The results shown in figures 9.10-9.12 indicate that two pulse standard PIV processing provides consistently high p.d.f. values (indicating a low spread in the majority of streamwise error values) at low errors across the simulated timescales. However, large,
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Figure 9.11: 1.0 viscous unit/pixel resolution streamwise velocity error contours of probability density function over different timescales ($\Delta T^+$), using two pulse and four pulse PIV algorithms. The red line shows the mean streamwise error.

Figure 9.12: 0.5 viscous unit/pixel resolution streamwise velocity error contours of probability density function over different timescales ($\Delta T^+$), using two pulse and four pulse PIV algorithms. The red line shows the mean streamwise error.
undetected spurious vectors at timescales $\Delta T^+ > 1.5$ bias the mean streamwise error results for this two pulse PIV algorithm. The four pulse ensemble correlation algorithm offers similarly consistent, low magnitude error distributions, and additionally produces a low mean streamwise error, uncorrupted by spurious vector biasing over the simulated timescales. This is likely to be a result of smaller particle pixel displacements from the chosen multipulse timing configuration outlined in figure 9.6, which have $1/3$ the displacement magnitude encountered by the two pulse algorithm. As $\Delta T^+$ approaches 2.5, two pulse displacements increase to the magnitude of the interrogation window size – which prompts a corresponding jump in processing error. While the four pulse FTC algorithm with a quadratic best-fit also exhibits uniform error performance across the simulated timescales, slightly greater spread in streamwise error is observed (causing a lower p.d.f. peak value), relative to the four pulse ensemble and standard two pulse processing algorithms. The four pulse pyramid technique (somewhat unexpectedly) shows significantly higher errors across the measured timescales than found when using the ensemble correlation (which is an algorithm that is closely related in structure), as well as the other processing configurations. However, pyramid correlation errors do reduce to lower magnitudes over longer timescales ($\Delta T^+$ of 2.0 to 2.5), reaching values which display greater consistency with the other tested correlation techniques.

### 9.2.3 Mean simulation errors - matched measurement interval

While the contours of the streamwise error p.d.f. comprehensively illustrate the spread of errors in each simulation scenario that is considered, direct numerical comparisons between the different PIV processing algorithms are difficult. The mean streamwise error (the red lines in figures 9.10, 9.11, and 9.12) show many of the same trends in error performance, and allow easy comparisons between the simulation cases. Figure 9.13 compiles the mean streamwise error from each PIV processing algorithm for the 1.5 viscous unit/pixel resolution simulations. Since the different timescales of these simulations result in changes to the particle displacement of PIV image pairs, which can also influence cross-correlation error, mean pixel displacements (averaged over the entire streamwise–wall-normal plane) corresponding to $\Delta T^+$ and $\Delta t^+_{4,n}$ timescales are shown in the secondary axes above the plot. Standard two pulse PIV processing (the blue line) corresponds to a mean displacement over the entire $\Delta T^+$ interval, resulting in relatively large pixel displacements over long timescales that may have contributed to the increases in observed mean error. The final pixel displacements of the pyramid algorithm (the red line) also correspond to the $\Delta T^+$ interval, since all lower correlation levels of the pyramid ($n < n_h$) are rescaled to the maximum time interval under consideration (corresponding to $n_h$). The ensemble
and FTC algorithms both correspond to the mean pixel displacements over the $\Delta t_{4,n}^+$ interval, resulting in smaller displacements that can explain the relative invariance of these streamwise error characteristics over the measured timescales. The standard two pulse and four pulse pyramid algorithms both experience larger changes in mean streamwise error, due to more disruptive variations in pixel displacements, which reach magnitudes on the order of the interrogation window size.

The mean streamwise error for each of the simulated image resolutions are compared in figure 9.14 to examine the relative changes in error behaviour. In all tested algorithms, except the pyramid correlation, increases in image resolution cause small increases to the mean streamwise error. Four pulse pyramid correlation processing displays the opposite trend, with reductions in mean error at higher PIV resolutions (excluding a deviation in the 0.5 viscous unit/pixel simulation at high $\Delta T^+$). The rescaling and averaging of correlation functions in the pyramid algorithm (applied to all $n < n_h$ levels of the correlation pyramid) relies on minimal local accelerations – therefore, improving spatial resolution may reduce the observed accelerations and produce lower error trends. A shift in the crossover location $\Delta T^+$, where a four pulse PIV algorithm
may out-perform standard two pulse PIV processing, is also observed with changing image resolution. These trends in the crossover point across all simulated image resolutions are summarised in table 9.2. As PIV image resolution increases (decreasing the viscous unit/pixel value), four pulse PIV appears to yield superior mean streamwise error performance, over a greater range of measurement timescales (under idealised measurement conditions), when compared with standard PIV processing. However, this result may be simply due to the greater particle pixel displacements which are encountered by the two pulse algorithm, when compared with the four pulse cases – a compromise and shortcoming of the chosen multipulse timing configuration.

Table 9.2: Summary of favourable four pulse PIV measurement timescales, when compared with standard two pulse PIV processing, based on mean streamwise error performance

<table>
<thead>
<tr>
<th>Resolution</th>
<th>1.5+/px</th>
<th>1.0+/px</th>
<th>0.5+/px</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Pulse Ensemble</td>
<td>$\Delta T^+ &gt; 1.1$</td>
<td>$\Delta T^+ &gt; 0.9$</td>
<td>$\Delta T^+ &gt; 0.7$</td>
</tr>
<tr>
<td>4 Pulse Pyramid</td>
<td>$\Delta T^+ &gt; 2.0$</td>
<td>$\Delta T^+ &gt; 1.7$</td>
<td>$\Delta T^+ &gt; 1.4$</td>
</tr>
<tr>
<td>4 Pulse FTC Quadratic</td>
<td>$\Delta T^+ &gt; 1.7$</td>
<td>$\Delta T^+ &gt; 1.5$</td>
<td>$\Delta T^+ &gt; 1.3$</td>
</tr>
</tbody>
</table>
9.2.4 Mean simulation errors - matched pixel displacement

The analysis thus far has assumed a timing configuration where additional laser pulses are inserted between fixed first and last pulses, resulting in a constant total measurement interval across both two pulse and four pulse simulations. This arrangement ensures the same total flow timescale is considered by each PIV algorithm for a fair comparison. Yet as a consequence of this decision, different pixel displacements are observed by some four pulse PIV algorithms (the ensemble and FTC algorithms) when compared with standard two pulse processing (and the four pulse pyramid correlation output). Therefore, for completeness, the simulation data is also replotted using an alternate “outside” multipulse timing configuration, where additional pulses add to the total measurement interval (see the timing diagram in figure 9.15). While the temporal extent of the studied flow varies between two pulse and four pulse PIV for this configuration (ie: $\Delta t_{2,1}^+ \neq \Delta t_{out,4,1}^+ + \Delta t_{out,4,2}^+ + \Delta t_{out,4,3}^+$), the pixel displacements encountered by many of the tested algorithms are now equivalent. The resulting mean streamwise error for the 1.5 viscous unit/pixel resolution simulation is shown in figure 9.16, with selected additional multipulse simulations performed (shown as the filled circles) to complete the parameter space.

In this alternative representation, where the multipulse measurements cover a total measurement interval of $\Delta t_{2,1}^+$ or $\Delta t_{out,4,i}^+ = 2.5$, the behaviour of the ensemble and pyramid correlations converge with each other, consistent with their similar underlying algorithm structure. The reason for this convergence lies in the impact of the signal-to-noise ratio criteria applied within the pyramid algorithm, which can limit the local height, $n_h$, of the correlation pyramid to prevent the signal-to-noise ratio falling below a value of 1.5. The frequency distributions of the local correlation pyramid heights, $n_h$, at each timescale, averaged over the simulation data sets, are shown in figure 9.17. White regions indicate the proportion of interrogation windows limited
Figure 9.16: Mean streamwise velocity error of 1.5 viscous unit/pixel resolution simulations over different “outside” timescales ($\Delta t_{1,1}^+, \Delta t_{out,4,i}^+$), using two pulse and four pulse PIV algorithms.

Figure 9.17: Local correlation pyramid heights, $n_h$, of four pulse, 1.5 viscous unit/pixel resolution simulations over different “outside” timescales ($\Delta t_{out,4,i}^+$).
to a pyramid height of $n_h = 1$, involving the correlation of only the 1-2, 2-3, and 3-4 PIV image pairs. The grey region relates to a pyramid height of $n_h = 2$, which involves 1-3 and 2-4 PIV image pair correlations in addition to the $n_h = 1$ image pairs. The black region, which is predominantly found at shorter timescales due to smaller associated displacements, represent a pyramid height of $n_h = 3$, where an additional 1-4 PIV image correlation is considered along with the other image combinations. At longer “outside” timescales, particularly as $\Delta t_{out,4,i}^+ > 2.0$, interrogation windows almost exclusively apply a correlation pyramid height of $n_h = 1$, which is identical to the correlations considered by the ensemble correlation algorithm (and why the mean errors of the two algorithms become very similar). Due to the increased total measurement interval of the “outside” timing configuration, image pairs associated with $n_h > 1$ at these longer timescales ($\Delta t_{out,4,i}^+ > 2.0$) experience very large pixel displacements which degrade the signal-to-noise performance, and may (in some cases) exceed the interrogation window size.

The error results from this timing configuration suggest that the FTC algorithm does not offer superior mean streamwise error performance to standard two pulse PIV at any of the simulated timescales. Meanwhile, the ensemble correlation consistently offers marginally lower error performance than two pulse PIV, whereas the pyramid technique provides lower mean streamwise error for $\Delta t_{out,4,i}^+ > 1.6$. 

**Figure 9.18:** Mean streamwise velocity error of 1.5, 1.0 and 0.5 viscous unit/pixel resolution simulations over different “outside” timescales ($\Delta t_{2,1}^+, \Delta t_{out,4,i}^+ \in [0.4, 0.8]$), using two pulse and four pulse PIV algorithms.
Investigation of results from the other simulated resolutions (shown in figure 9.18 for \(\Delta t^+_{out,4,i} \in [0.4, 0.8]\)), however, indicate that these trends are not maintained at higher resolutions. While smaller differences are observed between two and four pulse PIV mean streamwise errors at higher resolutions, four pulse mean errors also appear to grow faster than their two pulse counterparts (particularly at the 0.5 viscous unit/pixel resolution). Furthermore, mean four pulse ensemble correlation error exceeds that from standard two pulse processing for \(\Delta t^+_{2,1}\) and \(\Delta t^+_{out,4,i} > 0.6\) in 0.5 viscous unit/pixel resolution simulations – such that two pulse processing offers the lowest mean streamwise error of the tested algorithms for \(\Delta t^+_{2,1}\) and \(\Delta t^+_{out,4,i} > 0.6\) in the 0.5 viscous unit/pixel resolution “outside” timing configuration.

### 9.2.5 Overall assessment of multipulse performance

Based on the documented in-house implementations of the tested multipulse PIV algorithms over timescales of both \(\Delta T^+ \in [0.4, 2.5]\) and \(\Delta t^+_{out,4,i} \in [0.4, 2.5]\), four pulse PIV can generally offer only small improvements in error performance over standard two pulse PIV processing techniques. Matched pixel displacement mean error results (using the “outside” timing configuration) show error improvements on the order of \(\sim 0.1\%\) at a 1.5 viscous unit/pixel resolution (for ensemble correlation, as well as by the pyramid algorithm for \(\Delta t^+_{out,4,i} > 1.6\)). However, four pulse PIV error results deteriorate at higher simulation resolutions, possibly due to the compounding multipulse effect of larger pixel displacements at high resolutions, where they become less competitive with two pulse PIV performance. More favourable four pulse PIV error results are observed for \(\Delta T^+ > 1.5\) under a matched total measurement interval timing configuration (see section 9.2.3), although error behaviour is arguably distorted by mismatched particle pixel displacements and locally unoptimised normalised median test parameters. Insufficient higher order flow dynamics are present in the studied flow for the FTC algorithm to offer any performance benefits using four laser pulses, reinforcing the linearity conclusions from Chapter 8.

Despite mildly improved error performance when applying four pulse PIV measurements under select conditions, these simulations have only considered idealised PIV measurements, which have included uniform particles, the absence of any image noise, and crucially, perfect light sheet matching \((F_O = 1)\). Therefore, any modest advantages obtained from four pulse PIV experiments are likely to be obscured by measurement error increases, thanks to the greater complexity of the multipulse experimental setup. For example, since four pulse PIV requires the co-alignment of additional light sheets, there is increased potential for light sheet mismatch. Results from Chapter 7 suggest that an \(F_O < 0.80\) may be sufficient to overshadow the 0.1\% error improvement.
from multipulse PIV, corresponding to either a light sheet misalignment of $0.95\sigma$ or an equivalent uncorrected out-of-plane velocity component. Furthermore, only velocity errors have been considered in this multipulse PIV comparison – multipulse performance may vary when examining other common flow quantities considered in PIV measurements, such as vorticity. This extended examination of multipulse PIV sensitivity to flow quantities is beyond the scope of this study, but may be an area of future investigation. It was also demonstrated in Chapter 8 that turbulent flow linearity errors over common PIV measurement timescales have a relatively limited impact on results for both two and four pulse PIV configurations. Unless better multipulse algorithms designed to handle limited PIV burst image sequences (such as four image sets) can be implemented with improved error performance, the additional effort and complexity associated with four pulse PIV in wall-bounded turbulent flows does not appear to yield worthwhile benefits at the studied image resolutions.

9.3 Chapter summary

An error performance comparison of two pulse and a series of four pulse PIV algorithms has been investigated using synthetic PIV image simulations, to determine if limited-burst multipulse PIV techniques can offer practical improvements to a measurement. In-house adaptations of ensemble, pyramid and fluid trajectory correlation algorithms were applied to four pulse PIV image sequences for analysis over a variety of flow timescales and three image resolutions, producing the following conclusions:

- Lower image resolutions (larger viscous unit/pixel values) tend to exhibit lower mean streamwise errors.

- Under the tested implementation of the multipulse algorithms, the ensemble correlation consistently produced the lowest error performance of the tested multipulse techniques.

- Even under the idealised simulation conditions considered in this study, four pulse PIV techniques do not guarantee improved mean streamwise error performance. Under both timing configurations tested, there were resolutions and timescales where standard two pulse PIV methods offered the lowest mean error performance.

- The advantages of a four pulse PIV configuration can depend on the point-of-reference used in the comparison – if cases are to be compared using a matched measurement interval or a matched pixel displacement.
While some error performance improvements are observed in four pulse PIV simulations, compared with standard two pulse PIV processing, these advantages may be obscured by increases in experimental errors from the increased complexity of the four pulse measurement.
Chapter 10

Conclusions

Experimental error sources have the potential to generate the bulk of errors encountered in a PIV experiment. Therefore, thorough consideration and analysis of these error causes, and informed modifications to the experimental setup can yield significant improvements to the quality of a measurement. The investigations contained within this thesis have systematically examined the sensitivity and impact of several experimental error sources, to aid the ongoing effort to obtain low error, high quality PIV measurements.

Despite the increasing sophistication of today’s modern PIV experiments, the only fundamental hardware that is required for this technique is a combination of flow seeding, illumination, and camera imaging. These three areas are, therefore, a key focus when considering the contributions of experimental errors to a PIV measurement. Flow seeding characteristics have been well studied in the design and operation of various seeding apparatus (Kähler et al., 2002, for example), and compensation for camera imaging imperfections (such as image dewarping) can often be applied to captured images following a pre-experiment calibration procedure. The remaining key experimental element with the potential to severely impact experimental results is the illumination system, which typically involves the use of pulsed lasers. Chapters 4-7 of this thesis, therefore, focused on the important factors which can impact a laser’s performance in a PIV measurement.

10.1 The benefits of laser hardware adjustments

The most influential laser characteristic on experimental errors considered by this study proved to be the degree of matching between laser light sheet intensity profiles,
discussed in Chapter 7. A revised out-of-plane loss-of-pairs parameter, $F_O$, jointly developed with Bundeswehr University, Munich, was thoroughly studied using both synthetic PIV simulations with turbulent boundary layer DNS, and experimental wind tunnel measurements. Poorly matched or misaligned laser light sheets and severe out-of-plane velocity components were shown to rapidly degrade the correlation quality, as well as the error performance of the measured velocities and flow statistics. Two complementary techniques for estimating the $F_O$ characteristics of a measurement, using a laser profiling camera and by calculating the correlation/autocorrelation volume ratio, were experimentally verified and compared. Given the sensitivity of PIV measurements to light sheet mismatch, a minimum $F_O > 0.8$ was recommended for all PIV experiments to avoid any compromising mismatch effects.

The stability and transient effects of a laser, investigated in Chapter 6, were also found to have significant impacts on laser behaviour that could severely impact experimental errors if careful laser operating procedures are neglected. The causes and contributors to these transient characteristics were examined for a variety of pulsed laser systems, and a series of recommendations for laser operation to minimise the influence of these effects on PIV measurements were outlined. Provided that these guidelines are adhered to, however, the transient and stability characteristics of a laser should have a small and ultimately negligible impact on the errors in an experiment.

Both of these laser behaviours capable of dictating PIV performance were studied and examined with the aid of a laser profiling camera, outlined in Chapters 4 and 5. This device has been shown to be a valuable tool for quantifying laser errors, but also for performing general laser diagnostics, fault monitoring, and routine laser mismatch $F_O$ estimation. The low cost and ready availability of consumer camera equipment, explored in Chapter 4, now broadens the accessibility of these important tools for the improved quantification of laser characteristics and performance.

10.2 The benefits of multiple pulse PIV configurations

Minimisation of experimental errors alone cannot eliminate the errors encountered in a PIV measurement. Fundamental assumptions and performance characteristics of image processing and cross-correlation also contribute to a measurement’s error. Two pulse PIV is, by definition, constrained by only two measurement instants with which the displacement and velocity fields can be estimated. Consequently, only linear displacement estimates can be inferred from measurement data, which, depending on the flow and timescales of interest, can mask higher order flow dynamics. Chapter 8 explored the impacts of this flow linearity assumption on PIV measurement
errors for two, three and four pulse PIV configurations. However, results not only revealed that linearity errors are relatively small, but also that practical four pulse PIV configurations using a quadratic best-fit yield negligible advantages in capturing non-linear flow behaviours.

Given the fundamental limitations of two pulse PIV, increasing the captured data with additional measurement instants can enable improved characterisation of flow behaviours and greater filtering of measurement noise. Four pulse PIV configurations (multipulse PIV) were studied in Chapter 9, using idealised synthetic image simulations with a turbulent wall-bounded flow to investigate the potential benefits of this more sophisticated experimental approach. A selection of multipulse PIV correlation algorithms produced some modest advantages associated with multipulse measurements in many test scenarios. However, given the impact of laser mismatch and misalignment on PIV experiments (documented in Chapter 7), the measurement error advantages found using multipulse PIV configurations are likely to be obscured by experimental errors. This is due to the increased complexity of the hardware configuration required for multipulse PIV measurements, where a four pulse PIV measurement will likely require two PIV laser systems, and four individual laser light sheets must be rigorously matched in intensity and alignment. Results from Chapter 7 suggest that an $F_O < 0.80$ (a light sheet misalignment of $0.95\sigma$) is sufficient to overcome the observed gain in error performance from four pulse PIV. Therefore, while four pulse PIV may yield small advantages in specific use cases – depending on the image resolution, for example – the technique does not offer sufficient benefits under typical wall-bounded flow measurement scenarios to warrant recommendation based on this analysis.

10.3 Future work

The results from this thesis have inspired a number of areas for future investigation, to better quantify and reduce experimental errors. These additional avenues of future inquiry include:

- Further study of the image pre-processing impacts on the out-of-plane loss-of-pairs parameter, $F_O$, and verification that the correlation/autocorrelation volume ratio can correct for the impacts of this pre-processing procedure.
- Investigating the region of a laser light sheet’s intensity that significantly impacts the cross-correlation of an image pair. An understanding of this relationship between relative light sheet intensity (which would also be influenced by any
image pre-processing procedures) and the impact on correlation would allow an informed estimate of the “effective” thickness of an experimental light sheet. This thickness would determine the light sheet-normal spatial filtering and attenuation acting on the measured flow statistics, for improved comparison between measurement and simulation data.

- Applying other multipulse PIV algorithm implementations to the Chapter 9 simulations, as well as assessing the impact of adding further pulses (> 4) to the multipulse measurement burst sequence.

- Develop the use of lower cost, consumer cameras for double pulse, single exposure PIV imaging. While Chapters 8 and 9 both considered increasing data capture by introducing additional laser pulses to the PIV image sequence, increasing the resolution measured by two pulse PIV configurations can also reduce error by minimising in-plane velocity gradients and capturing the complete range of flow scales within a field of view. The reduced cost of consumer cameras allow high resolution, inexpensive, multi-camera arrays to be assembled for studying a given flow. In de Silva et al. (2018), a study in which I led the design and implementation of the camera hardware for the measurement, high quality double exposure PIV measurements were demonstrated using DSLR cameras. Further opportunities lie in extending this approach, by networking many small digital camera modules together in large multi-camera arrays.
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