

Beam stability and warm-up effects of Nd:YAG lasers used in particle image velocimetry

K Grayson¹, C M de Silva, N Hutchins and I Marusic

Department of Mechanical Engineering, University of Melbourne, Parkville, VIC 3010, Australia

E-mail: kristiangrayson@gmail.com

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Abstract

The characteristics and causes of Nd:YAG laser warm-up transients and steady state beam stability effects are investigated in this study. Dynamic laser performance has a particularly noticeable impact on particle image velocimetry (PIV) and other laser-based flow visualisation techniques, where changes in beam pointing can influence the overlap between laser light sheets and thereby degrade the correlation of PIV image pairs. Despite anecdotal knowledge or experience of laser warm-up effects, they have not been formally documented or quantified to date for PIV applications. In this study, the nature of these laser transients are analysed and compared among a selection of typical PIV laser equipment. An investigation into the cause of these transients during the laser warm-up sequence is also presented. Furthermore, the degree of dual cavity transient coupling within a PIV laser system is analysed to determine a practical limit to the laser light sheet overlap that can be expected from PIV experiments. Finally, the results from this study inform a series of recommendations for PIV best practice, which aim to minimise the impact of laser transients on experimental data.

Keywords: particle image velocimetry, Nd:YAG laser, laser beam stability, warm-up transients

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser beam drift and stability performance 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 [1]. 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. This study 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 [2]. 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

¹ Author to whom any correspondence should be addressed.

is documented by Fix and Stöckl [3] when investigating the coupled stability relationship between an Optical Parametric Oscillator (OPO) and its Nd:YAG pump laser. Siders *et al* [4] also briefly discusses 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 [5], Titanium:Sapphire [6] and Ho:YAG pumped OPO [7] 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* [8] 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.

2. Characterising laser warm-up transients

The warm-up transients of a laser system can be determined by studying the movement of the laser beam 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, a modular and flexible profiling system is used, consisting of a consumer digital camera and off-the-shelf components. Further details regarding this camera system can be found in Grayson *et al* [1].

Three different laser systems are considered and compared in this study. Lasers A and B are large, identical dual-cavity PIV lasers, whereas Laser C is a smaller, portable dual-cavity PIV laser system (see table 1 for additional laser specifications). Collectively these laser units cover a range of typical PIV lasers used in laboratory experiments. 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 is limited to approximately 0.2 Hz, laser

Table 1. Specifications of the laser systems considered in this study. The system age and flashlamp age relative to rated shot life are: Laser A (9 years, ~70% rated), Laser B (9 years, ~50% rated), and Laser C (5 years, ~15% rated).

Parameter	Laser A	Laser B	Laser C
Wavelength	532 nm	532 nm	532 nm
Energy (nominal)	400 mJ/pulse	400 mJ/pulse	200 mJ/pulse
Beam diameter	~9 mm	~9 mm	~6 mm
Repetition rate	10 Hz	10 Hz	15 Hz

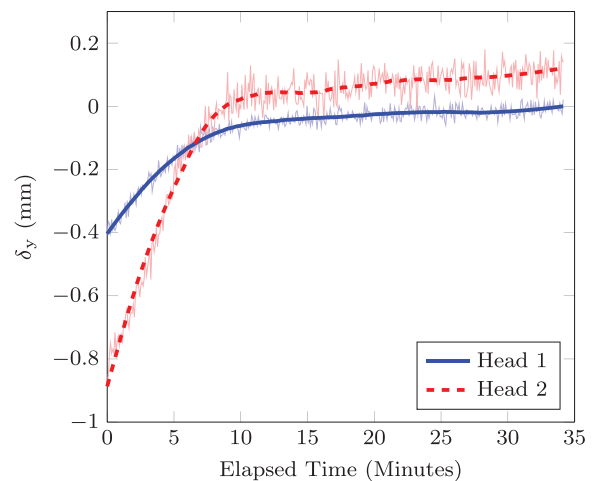


Figure 1. Comparison of vertical displacement from Laser A's heads 1 and 2. The faint lines indicate the shot-to-shot variation, while the thicker lines illustrate the filtered drift trend.

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 1 compares the vertical displacement (δ_y) of Laser A's head 1 and 2 weighted centroids during warm-up, as measured on 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 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 however, the warm-up transients from both laser heads do begin to stabilise after similar durations of about 15 min. 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

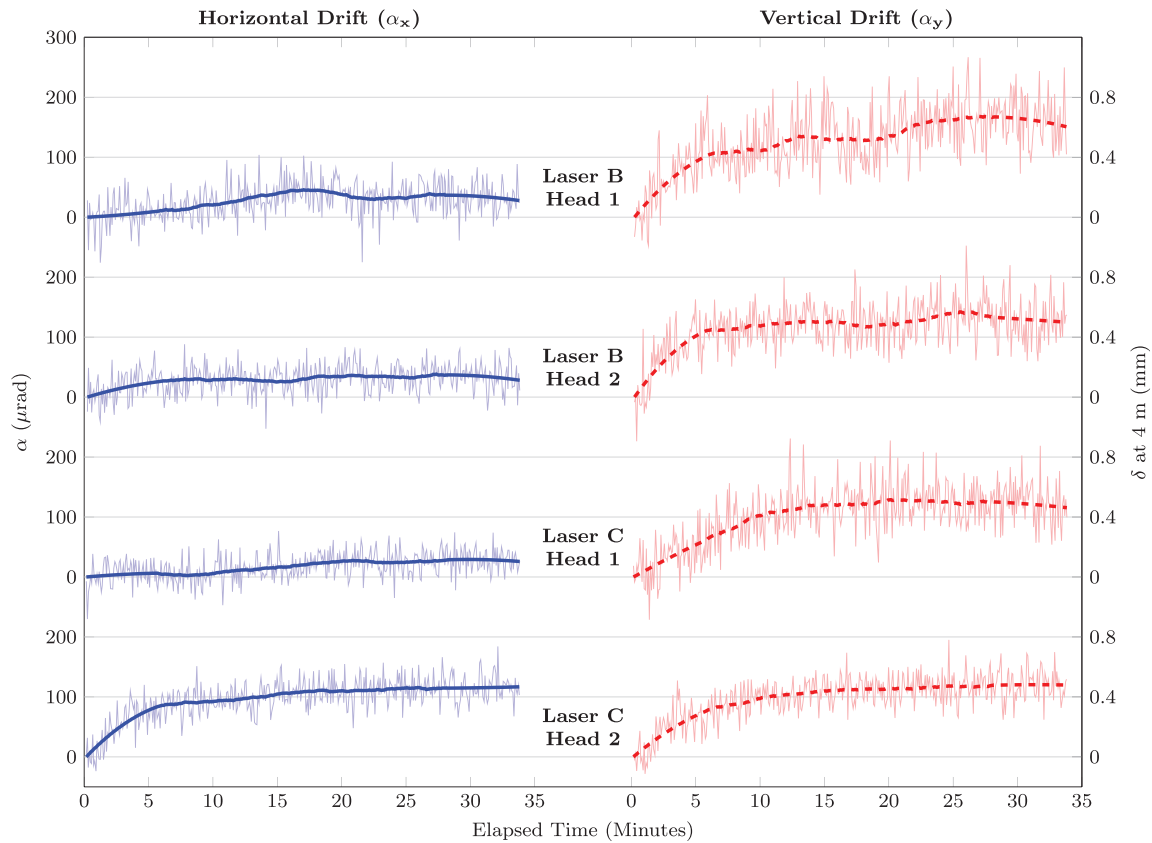


Figure 2. Angular laser beam movement of each laser cavity in Laser B (top two rows) and Laser C (bottom two rows). The horizontal and vertical drift is shown in left and right columns (and by solid blue and dashed red lines) respectively. The faint coloured lines show the shot-to-shot movement, while the brighter, thick lines show the filtered trend.

the laser reaching a state of equilibrium (<15 min 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 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 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 (α_x and α_y) 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 2. A representative physical shift over a 4 m beam path (δ_x and δ_y) is also included on the right-hand ordinate for reference. The vertical drift (α_y) of both lasers generally exhibit significantly more variable transient behaviour than the horizontal drift (α_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 3), 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 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. Despite these differences however, both lasers are largely stable after 10 to 15 min.

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 an unfocused laser beam can be defined by $\delta_{\max}/d \times 100$, where δ_{\max} and d describe the maximum drift and unfocused beam diameter in millimetres. Figure 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. 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.

3. 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 2. Case 2 consists of running the cooling system and laser power supply for 90 min 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 min 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 2 and the horizontal and vertical laser warm-up drift associated with these three scenarios is shown in figure 3. Cases 1 and 2 display very similar vertical stability

Table 2. Summary of laser subsystem states prior to warm-up transient tests (✓—system on, ×—system off).

	Cooling system	Laser power	Flashlamps	Q-switch
Case 1	×	×	×	×
Case 2	✓	✓	×	×
Case 3	✓	✓	✓	×

behaviour (α_y), depicting a large warm-up transient for the first 10 to 15 min of operation, consistent with the results discussed in section 2. 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 (α_x) and vertical (α_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 3 and Laser B in figure 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, thermocouples were placed on various laser cavity components to measure temperature changes during the warm-up sequence. While most of the laser system experiences slow, but steady heating during operation, 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 around the flashlamps is to be expected. Examining the difference between the temperature of the flashlamp housing and the surrounding laser componentry (shown by the red line in figure 4) 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 blue 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 min, 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

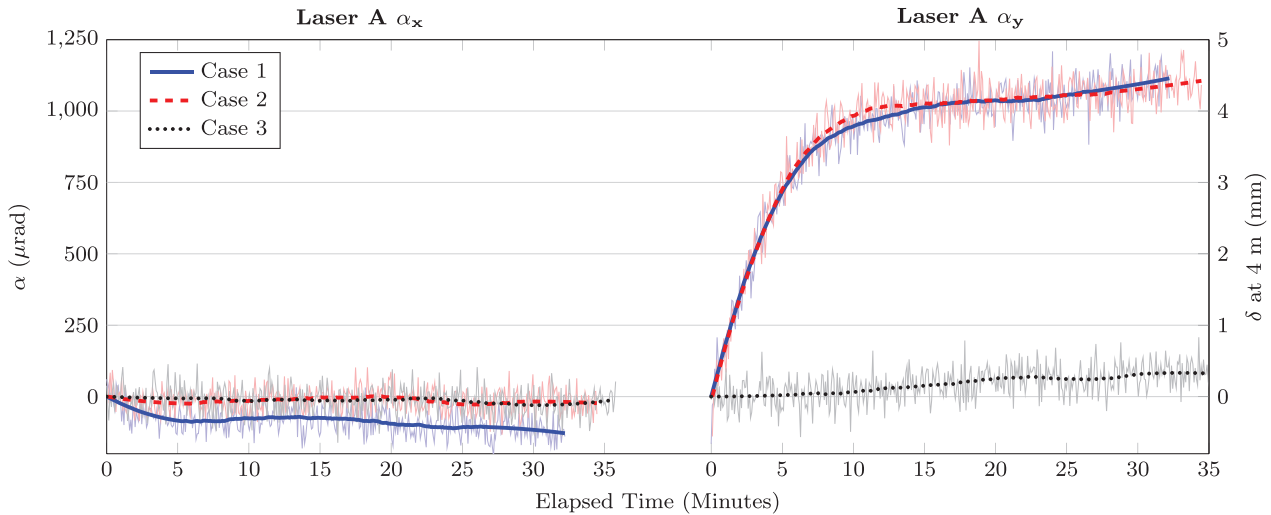


Figure 3. Angular beam movement during Laser A head 2 warm-up using three different laser subsystem start-up sequences. Horizontal drift is shown in the left plot, while the right plot displays the vertical drift. Faint lines show the shot-to-shot variation, while the brighter, thick lines indicate the filtered trend.

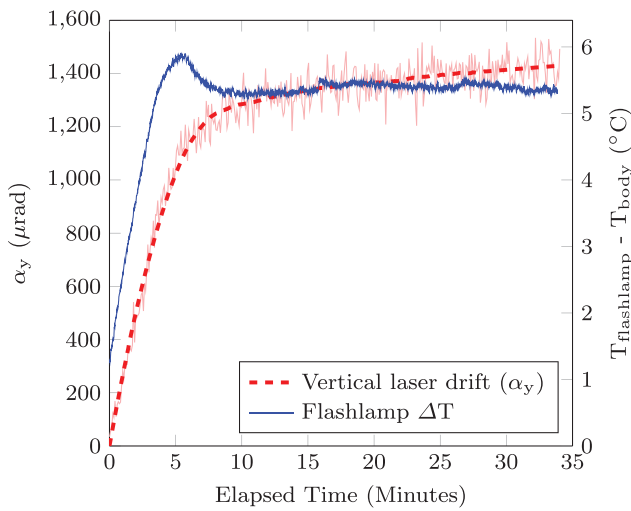


Figure 4. Comparison of vertical angular beam movement of Laser A head 2 run from cold (red lines) and the temperature difference between the head 2 flashlamp housing and the laser body (blue line). The faint red line shows the shot-to-shot beam movement, while the thicker red line shows the filtered behaviour.

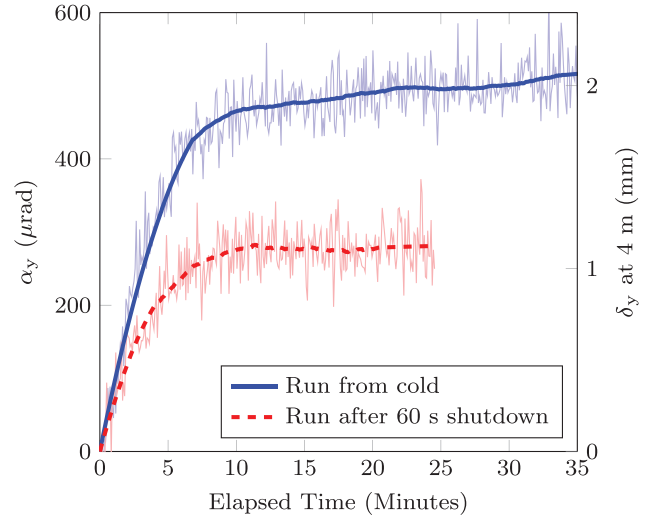


Figure 5. Comparison of vertical angular beam movement from Laser B head 1 run from cold (solid blue line) and after a 60s shutdown from an equilibrium state (dashed red line). Faint lines show the shot-to-shot movement, while the thicker lines show the filtered behaviour.

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, however complete shutdown of the system can reintroduce further transients on laser restart. To illustrate this behaviour, figure 5 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 60s 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 5, warm-up transients are present

irrespective of the shutdown duration and still require approximately 10 min 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.

4. 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. However 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

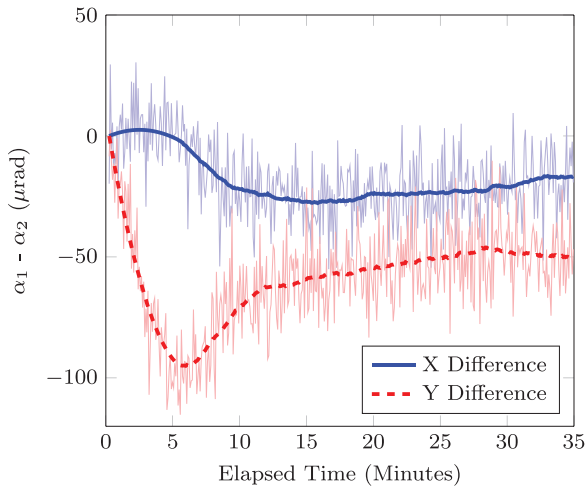


Figure 6. Relative angular drift between the two laser cavities within Laser B, run from cold. Faint lines show the shot-to-shot difference, while the thicker lines show the filtered behaviour.

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.

Rather than plot the drift of both laser cavities independently, changes in the relative separation of the two laser beams (by subtracting the 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. Variations in both the horizontal and vertical relative angular drift are observed over the first 10 to 15 min of laser operation, when the most significant beam pointing transients are also observed (discussed previously in sections 2 and 3). 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 3, 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 min 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

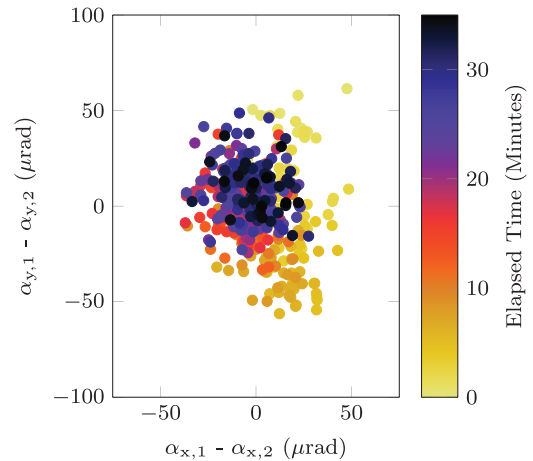


Figure 7. Relative angular drift scatter from Laser B, run from cold. The colour of each data point indicates how long the laser has been operating when the measurement was recorded.

the two laser beams when compared with their initial separation. These results are shown in figure 7, 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. 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 min of laser operation, a shot-to-shot relative beam pointing jitter remains (see figure 6). 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 min 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 $14.7\mu\text{rad}$ and $13.6\mu\text{rad}$ respectively. Therefore even if perfect mean overlap of the laser beams can be obtained, 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 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 small but non-negligible misalignment. Prior work on laser light sheet misalignment effects suggest that out-of-plane misalignments beyond approximately 25% of

the light sheet width can rapidly influence the correlation of images and the prevalence of spurious vectors [1]. 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.

5. 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 20–30 min 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. However 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. 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.
5. Complete shutdown of the laser system should be avoided during PIV measurements (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. Conclusions

An analysis of laser stability and warm-up transients has been presented, identifying the key laser stability factors that can

influence PIV measurements. A range of typical PIV laser systems have been examined, spanning a variety of flashlamp conditions and system ages. Clear evidence demonstrating the importance of correct laser warm-up procedures 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. An investigation of laser subsystem contributions to this transient behaviour reveals that laser flashlamp operation, and the resulting temperature imbalance within the laser chassis, play 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. The results from these investigations 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.

Acknowledgments

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