AN OPTICAL TIME RESOLVED MULTIPLE-PULSE PIV DIAGNOSTIC FOR VISUALISING TURBULENT STRUCTURES IN HIGH SPEED AIRFLOWS

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ABSTRACT

A unique new type of Nd:YAG laser has been constructed to produce a maximum of 10 ultra high-repetition pulses of 10mJ energy and 3 ns duration each with separation times adjustable from 1µs between consecutive pulses up to a total of 300 µs between the first and last pulse. This enables the development of time-resolved Particle Image Velocimetry for use in high-speed flows. The technique described here will allow a time-space correlation to be made and enable the measurement of coherent structures in turbulent flows.

INTRODUCTION

Classically turbulence is seen as a stochastic process, which is described by its statistical moments. This corresponds well to the view obtained from time-resolved single point measurements such as obtained with hot wire anemometry and Laser Doppler Anemometry (LDA). Flow visualization in turbulent flows however showed such flows not to be completely disorganized, but to contain large-scale ‘coherent’ structures [1]. As Brown and Roshko demonstrated [2], the instantaneous spatial structure and dynamics of the flow cannot be described by the turbulence statistics given by single-point probes, while flow visualization techniques such as Particle Image Velocimetry (PIV) can provide this information. Structures in a flow field can be characterized by their vorticity [3], as shown by e.g. Westerweel [1], which is therefore a crucial quantity to understand the dynamics of coherent flow structures.

Thus, for a description of the turbulent behavior of a flow both the temporal and the spatial evolution need to be considered, i.e. the spatio-temporal envelope [4]. Generally only a compromise can be obtained, especially in high-speed flows. Although advances are made using 2-point LDA, such point measurement techniques still require a prohibitive amount of time for full field mapping, and do not provide instantaneous full-field information. Recent work by Bridges *et al.* [5] has shown that by using PIV measurements the power spectra of high-speed flows can be obtained, though still requiring long measurement times and without obtaining the temporal evolution of structures. However, with the advent of new types of laser, progress in camera technology and the rapid increase in computing power it is possible to envisage a measurement approach which can provide new insight in dynamic processes such as vortex breakdown.

The new laser system described here, which facilitates time resolved multiple-pulse PIV, has been assessed in a preliminary test on a subsonic flow to observe the effect of vortex generator jets [6] on boundary layer separation. The example provides a demonstration of the applicability of time-resolved PIV to the study of large-scale eddy structures. In the experiments four pulses were generated, two pulses were captured in the first frame of the camera and two pulses in the second frame of the camera. The velocity field is obtained using autocorrelation in each of the two image-frames. Further velocity information is obtained using cross-correlation on the two images. Thus a short time series consisting of 3 velocity-vector sets is obtained of the velocity distribution, implicitly removing the directional ambiguity associated with autocorrelation techniques.

NOMENCLATURE

LDA: Laser Doppler Anemometry
PIV: Particle Image Velocimetry.

PARTICLE IMAGE VEOCIMETRY

Vorticity is an important parameter in understanding the dynamics of coherent flow structures [1]. Vorticity is defined as the rotation of the velocity field, and is thus obtained by differentiation of the velocity vectors. Coherent structures can then be defined as areas with a vorticity value above a certain threshold. This is illustrated in Figure 1, where PIV data is shown obtained in a boundary layer flow. Based on the vorticity, a clear separation region can be identified. To obtain information on these structures the measurements need to give: 1. sufficient resolution to resolve the vortices in the flow, 2. a temporal resolution that matches the time scale of the flow, in order to study the dynamics of the structures, 3. sufficient accuracy in the velocity measurements as the errors in the velocity strongly increase the errors in vorticity as this is obtained by differentiating the velocity data.

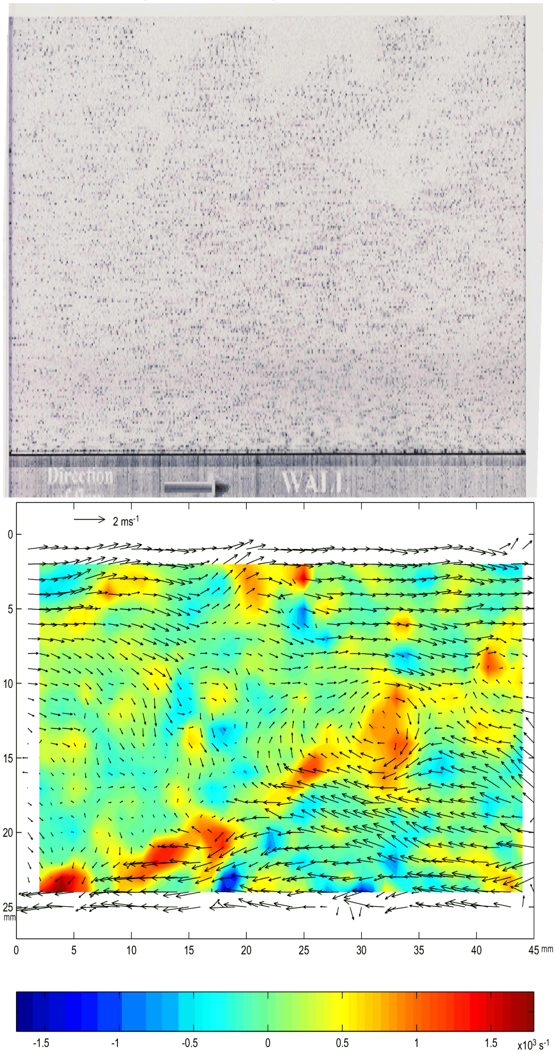

Figure 0: PIV measurement of separating boundary layer flow. Top: Raw photograph, Bottom: velocity field (arrows) plus superimposed vorticity (colour).

Particle Image Velocimetry (PIV) has a major advantage over other flow measurement techniques in that it provides the instantaneous spatial measurement of velocity in a full planar cross-section of a flow. The technique appears very simple. Particles are put in a flow and are illuminated twice by a light sheet (usually from a laser source). The two instants are recorded using cameras and the displacement of the particles between the two flashes is then determined to obtain particle velocity (speed and direction). In PIV the particle density is so high that particles cannot be tracked individually, although they are individually distinguishable (see e.g. top Figure 1). Therefore the velocity in each region is determined by obtaining the average displacement in a small interrogation area using a statistical method. If both flashes are recorded in a single image, the average displacement in each part can be determined through the spatial *(auto-) covariance* function. This results in a self-correlation peak plus two displacement-correlation peaks at equal opposite distances. The center of each displacement peak yields the local-average, in-plane displacement of the particles. The disadvantage of this approach is that the displacement is only obtained with a 180-degree directional ambiguity. This ambiguity is avoided when each light-flash is recorded in a separate image. By using the *cross-covariance* function for these two images a single peak is found indicating both magnitude and direction of the (local-average) displacement [1].

<u>PIV in high-speed flows</u>

A basic assumption of the PIV technique is that the particles that are detected follow the flow, i.e. the velocity of a particle at a point in the flow is the velocity of the flow at that point. For this assumption to be valid the particle-size in high-speed flows (velocities in the region of 300 m/s) is limited to about 0.2µm diameter. Visualizing individually resolved particles thus requires high-magnification optics. Furthermore, obtaining homogeneous seeding throughout the field can be cumbersome, with some flow regions (e.g. recirculation areas) being only very sparsely seeded. In these sparsely seeded regions often only a few velocity vectors can be obtained, therefore only providing measurements at low-resolution. Thus, collecting sufficient data to measure turbulent structures present in the flow can be difficult. An example is shown in Figure 2, where a vorticity plot is obtained based on sparse PIV data around a rotor blade. The structures in the wake of the blade can only just be identified.

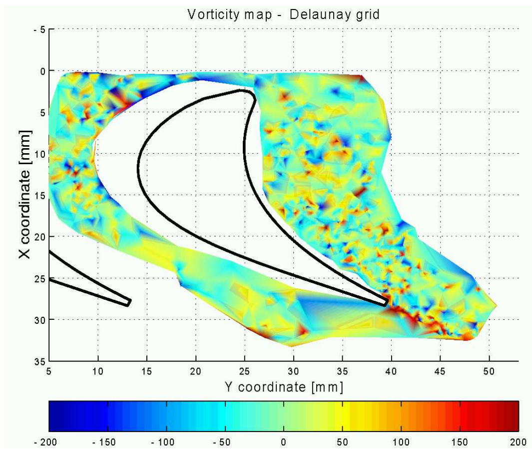

Figure 2: Vorticity plot in high-speed flow around rotor blade obtained from PIV. The results are plotted on a Delauney grid; note the sparse sampling at the bottom of the blade.

A further complicating factor in identifying turbulent structures from PIV data is that PIV measurements are generally obtained at relatively low repetition rates, which are governed by the repetition rate of the laser flashes and the data-capture rate of the cameras used. Thus, the sequential velocity measurements are unrelated and therefore do not provide a direct image of the dynamics of coherent structures in the flow, complicating identification of possible structures. The low repetition rate furthermore means that obtaining sufficient data to allow statistical turbulence data to be extracted requires unrealistic rig-running times. Thus, generally in high-speed flows it is difficult to provide a suitable number of measurement points for turbulence analysis.

To allow this kind of measurements to be obtained in high-speed flows a solution is proposed and demonstrated which provides multiple pulses to record time-resolved PIV video frames.

TIME-RESOLVED PIV

To study high-speed flows, images must be taken by exposures short enough to 'freeze' the image of the particles, to avoid movement blurring. This is either achieved by using a short camera exposure time, or by using very short light pulses. Furthermore, in order to temporally resolve the dynamics of structures in turbulent high-speed flows, subsequent pulses must be at intervals short enough to match the time scales of the flow. For velocities of the main flow in the order of 300 m/s the vorticity structures will typically be traveling at 70% of this, i.e. ~200m/s [1]. For a typical visualization area of 200 x 200 mm^2 this means structures will have traveled the length of the viewing area in 1 ms. Thus, to resolve the dynamics of coherent structures several images will need to be captured within this time-range. Note that the vortices move significantly slower than the tracer particles (which take ~0.7ms to pass through the visualization area when traveling at the mean flow velocity). Furthermore, the images need to be obtained at sufficiently high-resolution, preferably at least 1024x1024 pixels.

Thus, possible variables to obtain time-resolved PIV are multi-pulse laser technology to obtain flashes at the required repetition rate, seeding size and delivery, image intensification to acquire images of the extremely small particles which reflect little light, and PIV camera technology.

The development of the time-resolved particle image velocimetry system described here consists of two (related) parts: light source and image-capture system.

Light source

To generate a light sheet that is of suitably short duration to freeze the particle motion and that is of sufficient intensity several options exists. Several double pulses lasers, of 50-100mJ/pulse each, can be combined to generate a set of double pulse images. Similarly a number of single pulse lasers could be combined to generate a sequence of consecutive pulses at short time intervals. The option that was chosen in this project was to create a new type of multi-pulse Nd:YAG laser. This has been achieved by modifying a conventional Nd:YAG laser in cooperation with InnoLas (UK) Ltd. Using newly developed solid state switching technology it has been possible to provide up to 10 pulses of equal intensity. Currently a maximum energy output of 10mJ per pulse has been achieved, with a maximum separation of 300μs between the first and last pulse and 3ns duration per pulse. Typically this time-span would allow tracking a structure over ~1/3 of the viewing area. The minimum separation time between pulses is 1μs. The pulses can be externally triggered allowing coupling to current CCD digital camera technology.

Image-capture system

To capture all images generated by the laser pulses a camera (-system) is needed that is capable of storing up to 10 PIV images at microseconds intervals. Although currently high-speed CMOS cameras are available, they generally still only provide images at frame rates up to 1000-2000 fps at a useful high resolution (1024x1024 pixels, e.g. Ultima APX, Oxford Lasers). Currently commercially available Charge Coupled Device (CCD) cross-correlation PIV cameras allow the capture of two separate images at microsecond down to 200 ns intervals by triggering the light pulses to occur one at the end of one camera-frame and the second at the start of the next frame (frame-straddle, e.g. Dantec, TSI, LAVision). However, as the camera-shuttering can only be done on one frame, in this case the camera still captures all light present during the exposure of the second frame. If only two light pulses are present, only two 'frozen' images are obtained. However, when more light pulses are present during the camera exposure time, the images of several light pulses will be overlapping in a single frame. Thus if a sequence of pulses are used the first one or two pulses can be recorded separately but the remaining pulses are all captured in the second frame. Consequently, the standard PIV analysis techniques described earlier cannot be used. The problem can be solved by using a set of cameras combined with image intensifiers that can act as fast shutters. A higher quality solution would be the use of phase-plate cameras, though at an increased price. As will be shown in a later section, the number of cameras can be limited by using a new type of analysis, based on both auto-correlation as well as cross-correlation.

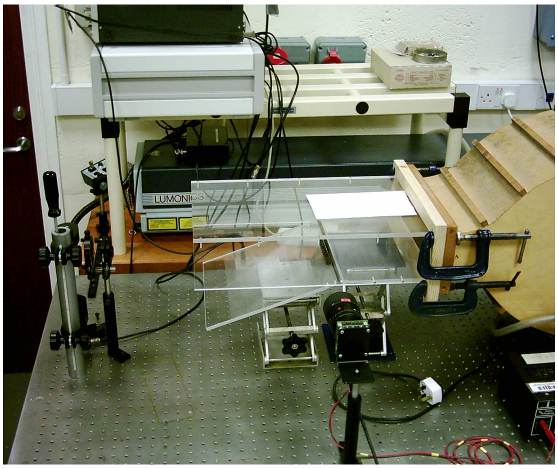

Figure 3: Experimental set-up for vortex generator jet studies in low speed wind tunnel flow. The tunnel is shown on the right, with the Perspex test section in the centre. The PIV camera views the flow from the side (front), with the laser light sheet sent in from the left. The jets are generated at the junction of the flap and the flat part of the test section.

EXPERIMENTAL SET-UP

Preliminary results were obtained to demonstrate the expected capabilities in providing time-resolved PIV measurements using the multi-pulse laser system. The investigation was performed in a low speed flow as a readily available facility. Furthermore, testing in a low-speed flow allows illustrating the advantage of multi-pulse data-capture in providing turbulence information using conventional PIV cameras.

Vortex generator jets

The test flow was a configuration designed to observe the effects of vortex generator jets on boundary layer separation. Flow control has been widely used in aerodynamic applications to reduce and prevent separation. Examples of flow control devices are vaned diffusers and leading edge vortex generators on airfoils. These methods are considered passive, as they cannot be adapted to improve performance for different flow criteria. An active system will be able to adapt to time varying changes in the flow.

It has been shown that blowing through discrete jets located near the leading edge of an airfoil can forestall separation [6]. The mechanism by which this is achieved is through turbulent mixing. The jets promote mixing between the high-speed bulk-flow and the lower speed boundary flow. The interaction of these two flows generates vortices that are responsible for the mixing. The mixing can delay separation or avoid it altogether.

Experiments were performed in a low speed wind tunnel. The flow was generated using a centrifugal blower connected to the upstream end of the facility. The flow at the exit of the wind tunnel (start of test section), is parallel to the upper wall of the test section, traveling at ~13m/s. The velocity of the bulk flow was measured using a manometer and compared with results obtained using PIV methods. The test section is made of Perspex and consists of a rectangular box, of which the lower floor is hinged to produce a test section with variable angle of wall divergence (Figure 3) inducing boundary layer separation. The bottom plate contains an inset containing eleven 1mm diameter holes placed equidistantly along the width of the flap (visible as black strip in Figure 3). These holes are connected to an air supply, pressure regulator and pulse generator. The pulse generator produces either a constant or a pulsed jet just ahead of the separated flow region. By varying the pulse rate and strength of the injected jet it is possible to affect the boundary layer separation of the main flow[7]. The jet effectively ‘fills’ in the region of the flow created by the divergence of the exit flap.

Figure 4: Constant jet flow generated at 0.5 bar. Main flow direction: right to left. 10 pulses from laser captured on single camera frame, 9 µs between each pulse.

PIV system

The laser is set-up along side the wind tunnel (Figure 3). The beam is steered using a series of mirrors and expanded by a cylindrical lens and focused using a biconvex lens forming a sheet of approximately 0.5 mm thickness. The light sheet is steered orthogonally to the lower and upper walls of the test section (Figure 3) and the camera is placed perpendicular to this, with the imaging lens (f11 macro-lens, at 150 mm from light sheet) focused on the light sheet. The flow is seeded using an aerosol of smoke detector spray. The particles are between 10-20µm in diameter and remain buoyant in the air for approximately one hour.

RESULTS

Two types of image capture were performed. First all pulses were captured in a single image frame to illustrate the laser-capabilities. Secondly, images were captured in multiple image frames and data was obtained using a special analysis.

Single image frame

Figure 4 shows the raw result for a constant free jet flow as used in the jet vortex generator experiment, when all 10 laser-pulses are recorded in a single image frame. Although this does provide a feel for the flow behavior, obtaining quantitative information is difficult. Particles may move in and out of the plane of the laser-sheet and the direction is not obvious (especially in turbulent flows as this jet).

Therefore, to enable data-processing, while using camera technology currently available, a combination of conventional cross-correlation and auto-correlation is used (Figure 5).

Multi-frame analysis

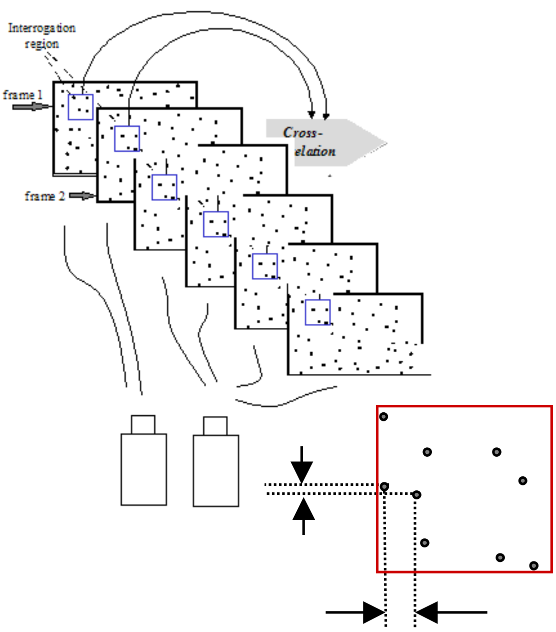

Figure 5: Multi-pulse PIV analysis with reduced number of cameras using cross-correlation between frames plus auto-correlation within each frame.

Figure 6 shows a vorticity plot for the same jet, but now recorded using four pulses that were captured in two separate frames. Two pulses were captured in the first frame of the camera and two pulses in the second frame of the camera (Figure 5). There was an equal time-delay between the four pulses. The velocity field is obtained using autocorrelation in each of the two image-frames (Figure 5). Further velocity information is obtained using cross-correlation on the two images. This is

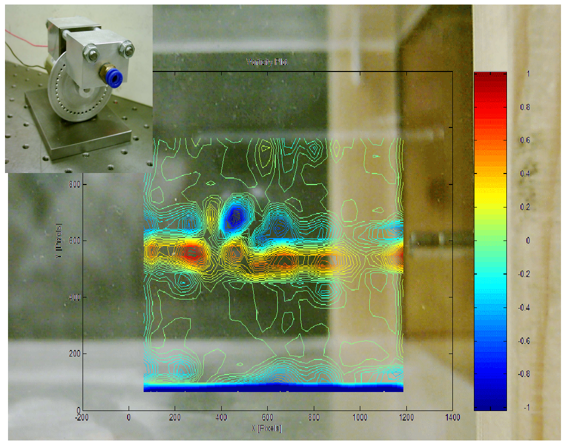

Figure 6: Vorticity plot of pulsed jet (cf. Fig. 4), superimposed on background image showing nozzle exit on the right. (Inset: jet nozzle.

made possible by identifying the first and second positions of the particles in the auto-correlation of each frame separately, and then using only the set of second particle positions for frame one and only the first particle positions in frame two. Thus a quantitative analysis is possible, where a short time series consisting of 3 velocity-vector sets is obtained of the velocity distribution, implicitly removing the directional ambiguity associated with autocorrelation techniques.

Further experiments were performed with the new multi-pulse PIV-system to analyse the vortex generator jets in the subsonic boundary layer flow. Figure 7 shows results for three flow conditions: separation with no jet exhaust, constant jet exhaust and pulsed jet exhaust.

The results in Figure 7 show the vorticity and velocity vector plots for the 20-degree plate. For the no injection case the boundary layer separation occurs at a divergence of the lower wall of between 15-20 degrees. The separation is dominated by large vortex structures.

For the constant exhaust jet case reattachment of the boundary is expected just downstream from the viewing area of the experiment. The vortices caused by the jet are visible and notably smaller in size than that in the no-injection case.

In the case of the pulsed jet the boundary layer is highly agitated. Many small vortices are generated and carried down stream with the bulk flow. It can also be seen that the injected jet has minimized the extent to which the turbulent structure within the separated region has penetrated the main flow. The controlled flow injection has effectively ‘filled in’ the negative incidence divergence created by the flap.

Although the images shown in the paper seem to represent conventional PIV results, the obtained

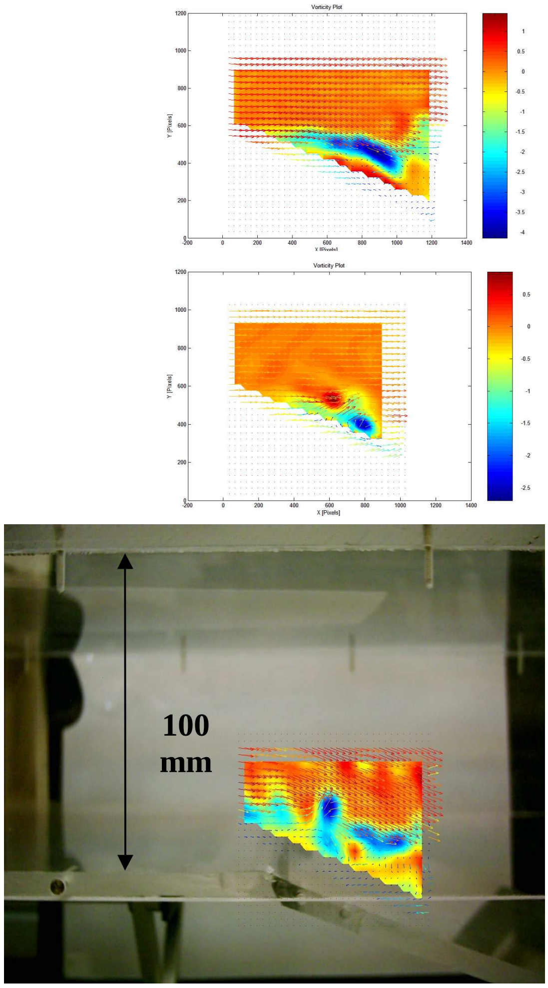

Figure 7: Velocity plots with superimposed vorticity plots for bottom plate at 20-degree downward inclination. Main flow direction: left to right. Top: no injection, Middle: continuous jet injection, Bottom: pulsed jet injection. (Bottom image superimposed on image of wind tunnel test section).

data can be animated in time-sequential sets, which do aid in interpretation of results such as shown in Figures 6 and 7. The time-resolved PIV helps in clarifying e.g. the behavior and extent of the vortices in Figure 7 c, and furthermore provides derived information such as acceleration, which cannot be obtained from conventional PIV data.

CONCLUSIONS AND DISCUSSION

A high-speed PIV visualization system capable of capturing a series of nanosecond duration snapshot images at microsecond intervals has been demonstrated. Using this approach highly dynamic flow events can be effectively ‘frozen’, sequenced and temporally tracked.

To obtain PIV measurements in high-speed flows is problematic. Firstly sparse seeding in turbulent areas can provide low resolution and ambiguous measurements. Secondly, in order for the particles to follow the flow the seeding particles need to be small, typically 0.2 micrometer. Finally, the imaging of sub-micron particles is problematic as they reflect less light, thus requiring higher sensitivity of the image capturing system, while also demanding very short illumination/image capturing times to prevent image blurring or streaking.

Commercial PIV measurement systems are available that can provide two images at microsecond intervals using pulsed lasers as illumination source. Although these do provide velocity distributions at different moments in high-speed flows, only separate instantaneous velocity distributions are obtained, which do not allow temporal tracking. Temporal tracking would reduce the problems due to sparse seeding and facilitate identification of so-called coherent structures, such as large-scale mixing structures found in gas turbine exhausts, which are relevant for engine efficiency and noise production.

For the multi-pulse PIV system described in this paper a unique new type of Nd:YAG laser has been constructed to produce a maximum of 10 ultra high-repetition pulses of 10mJ maximum energy and 3 ns duration each with separation times adjustable from 1μs between consecutive pulses up to a total of 300 μs between the first and last pulse. This enables the development of time-resolved Particle Image Velocimetry for use in high-speed flows. To reduce the cost of the camera system, data is captured by storing pairs of two consecutive pulses in one image frame, with the subsequent pair being stored in the next frame. To obtain velocity vectors autocorrelation is used on the double-exposure frames. In this process, each particle is identified as being captured in the first light pulse or in the second. Then, based on these particle groups, cross-correlation between the consecutive images (using only the relevant particles, identified in the auto-correlation step) is used to obtain an extra velocity vector representing the movement between e.g. pulse 2 and 3. The technique described here will allow time-space correlations and enable the measurement of spatial structures in turbulent flows.

The preliminary results shown provide a demonstration of the applicability of time-resolved PIV to the study of large-scale eddy structures, similar to those typically found in jet mixing layers. It demonstrates how multiple PIV images can be captured and processed and how these can be used to obtain vorticity data. Although presently results are only obtained in low speed flows, extending the technique to high-speed flows is straightforward.

With the increased amount of data, automated data collection and processing become essential. Also, representation of this data, which is three-dimensional with an added time dimension, is nontrivial. Further research into optimal use of camera technology as well as the data-handling is currently taking place.

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