Feasibility study of three-dimensional PIV by correlating images of particles within parallel light sheet planes

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Abstract: One approach to obtain information about the out-of-plane velocity component from PIV recordings is to analyze the height of the peak in the correlation plane. This value depends on the position of the particle image plane, which (and depends on the out-of-plane velocity component) and on other parameters. To circumvent problems with other influencing parameters and to determine the height of the peak in the correlation plane, we present a method for peak height evaluation. Our experimental results show the feasibility of an out-of-plane velocity estimation by analyzing images of particles within parallel light sheet planes by spatial cross-correlation.

List of symbols:
- \( \rho \) : particle density in the flow
- \( r \) : particle image diameter
- \( I \) : image intensity
- \( z_1, z_2 \) : distances of the two light sheets from the sample plane
- \( R_{(r)} \) : correlation function of the image displacement
- \( \phi(r) \) : correlation function of the cross-correlation function

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1 Introduction

One limitation of the application of conventional particle image velocimetry (PIV) is its inability to resolve the out-of-plane components of velocity vector fields. Since most
of the technologically important flows are three-dimensional, the application of PIV to these flows is rapidly growing. To overcome the chromatic aberrations, a novel idea to increase the use of phase component in PIV is described in this paper.

The approach is based on the quantitative analysis of the light from the evanescent peaks. A qualitative analysis of the peak height in conventional PIV has already been used by Lipton and Grady (1991) to derive the core boundary of a jet flow. Our aim was to test the concept of relating the behavior of the evanescent in the region of the particle normal to two recorded planes as an expression. The concept is illustrated by a phase

Scientists Agarwal et al. (1994) have proposed a novel technique to determine the three-dimensional velocity field in the flow. The technique uses two cameras without phase-locked illumination and two cameras to record the light from the evanescent peaks. The concept is illustrated by a phase

of operation

Particle motion through parallel light sheets

The plume of smoke forms an important component of the measurement volume, as discussed above, and for the light sheet given in Fig. 1a. To simplify the following explanation, we assume that the light sheet is oriented only in the direction of the jet. The plume represents a particle, which moves in the interrogation volume during the exposure time.

When dealing with a finite number of particles in the interrogation volume, the number of particles image pairs per interrogation cell can be used to estimate the out-of-plane phase component. This number is proportional to the number of particles within the interrogation volume, i.e., the number of particles within the interrogation volume at t, (see Fig. 1a), decreased by the number of particles lost in the interrogation volume at t1, (see Fig. 1b), and the number of second image lost due to one of the phase-locked illumination. The number of image pairs per interrogation cell is calculated as

\[
N = N_0 - N_1
\]

where

\[
N_0 = \frac{N_1}{C}
\]


Fig. 1(a). Side view of the arrangement of the particle at the time of the second exposure of a single particle. The particle is arranged in the center of the camera field. The light sheet passes through the center of the particle.

Fig. 1(b). Side view of the arrangement of the particle at the time of the third exposure of a single particle. The particle is arranged in the center of the camera field. The light sheet passes through the center of the particle.

The arrangement of the particle is the same as in Fig. 1(a). The particle is arranged in the center of the camera field. The light sheet passes through the center of the particle.

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The influence caused by this decomposition are the correlation of the mean intensity distribution $R_{12}(u,v)$, the fluctuating noise component $R_{13}(u,v)$ (represented by images of distant particles), and the correlation peak giving the image displacement $R_{14}(u,v)$ of identical particles. The basis of the evaluation procedure is used to detect the intensities of the images of the particles in different light sheets $R_{14}(u,v)$ is approximated by

$$\frac{1}{n} \sum_{i=1}^{n} I_i(u,v).$$

We eliminated two of the above mentioned effects by subtracting the mean intensity of the interrogation window and by measuring the correlation peak height with perfectly matching images of the distant particles. In the case of matched images, the following simplifications are applied in formula (1):

$$R_{13}(u,v) = \frac{1}{n} \sum_{i=1}^{n} I_i(u,v) = \frac{1}{n} \sum_{i=1}^{n} A_i(u,v).$$

The high intensity profile of the light sheets in a direction $z$ has been assumed instead of a constant denominator. The fact is true that $R_{14}(u,v)$, which is the normalized correlation of the intensity distribution $I(x,y)$, is a function of two successive planar light sheets, as a function of the location of the interrogation window, and as a function of the size of the interrogation window.

The correlation peak $R_{14}(u,v)$ is approximated by a triangle function. The size of the correlation peak $R_{14}(u,v)$ is assumed to be identical for both correlation. This is only a rough approximation as long as the distance $z$ and $2z$, or an optimal range $z$ is used.

The conclusion of the measurement accuracy can be reduced by averaging results over neighboring interrogation cells. However, this has to be balanced against a decrease in spatial resolution.

4. Experimental setup.

To evaluate the properties of the velocity estimation given in equation (4) we performed a single material simulation assuming a Gaussian intensity distribution of the particle images on this background. The locations of the particle images are three frames of a particle moving with a velocity vector $\mathbf{v}$.

A computer was used to simulate the correlation of two successive planar light sheets, as shown in Fig. 6. From the correlation results, the peak height $R_{14}(u,v)$ can be found to be the product of the intensity of the particle images in the central plane $I_0(u,v)$, the velocity vector $\mathbf{v}$, and the location of the interference pattern $z$. This is why we used the sum of all gray values contained in the peak to be evaluated with a threshold $P_0$ for detecting the velocity vector $\mathbf{v}$.

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The setup was designed to observe the motion of three-dimensional particle paths using three-dimensional particle imaging. The setup was constructed using a laser, a camera, and a lens to capture images of the particle motion. The laser was used to generate light pulses at a wavelength of 632.8 nm. The camera was positioned to record the images of the particle motion. The lens was used to focus the light onto the camera. The setup was designed to capture images of the particle motion at a rate of 1000 frames per second. The images were analyzed to determine the particle motion and velocity.
Experimental results

To obtain more information about the flow field generated by the setup described above, we first took PIV data along the centreline of the vortex ring (Fig. 8).

The axial components of the velocity vectors along the inclined line give information on the cut of plane velocity component we had to expect when observing the flow field. The ratios of the component of the axial velocity perpendicular to the centreline and parallel to the ring's axis are shown in Fig. 9. Following the described method, we then captured images of particle velocity profiles light sheets at three different locations. Both light sheet planes were orientated perpendicular to the vortex ring axis as shown in Fig. 9. The lines were evaluated by correlating 2 with 3, 2 with 4, and 2 with 5, directing the correlation programme to calculate the innovation of both measurement planes at the location for each.
The size of the interrogation windows was 13 × 13 pixels and the interrogation step size in both the x and y directions was 1 pixel. The results of the evaluation of the frames J and J* containing images of particles within the same flow field show surfaces in a ring near the center of the flow field (see Fig. 6). This area of low correlation probability is not a true region of low correlation but is due to misalignment of the ring and the section of plane motion in the center of the observed field.

The positions of the null peaks in the cross correlations plane χ1z(x, y) are shown in Fig. 11. They clearly show the influence of the out-of-plane velocity component (i.e., low correlation peak heights in the center of the cross range).

The results of the evaluation of the frames J and J* show surfaces in a ring further inside (see Fig. 11). The values of the height of the correlation peaks χ1z(x, y) are shown in Fig. 12. The peaks are due to the contribution of the velocity components outside the correlation peak heights.

The following evaluation procedure was used to further enhance the results of the images captured in different planes. The intensity distribution χ1z(x, y) of the correlation of the frames J and J* and the intensity distributions χ1z(x, y) of the correlation of frames J and J* with compared added to (x, y) compared to the correlation of frames J and J* with compared added to (x, y) were used to form the correlation image χ1z(x, y) compared to the correlation of frames J and J* with compared added to (x, y).

Fig. 11. Cross-correlation peak heights of images of particles taken in the same flow field captured by a spatial moving (x, y) based for the representation.

Fig. 12. Velocity vector map obtained by image of particle illustrated by different light shade.
The final result is shown in Fig. 14 in a three-dimensional representation.

4. Conclusions

In this study, we demonstrated the feasibility of using information encoded by the correlation function to measure the out-of-plane components of velocity fields. Among the methods tested, the proposed correlation technique is superior for the described dual-plane correlation technique due to the correction of PTV. This becomes clear if considering that a single particle image pair gives only linear information into which of the two light sheets the particle moved. The presence of a drastically observable maximum of the image density therefore results in a linear spatial resolution and/or accuracy compared to the in-plane measurement. Furthermore, the limits of the equation given in Sect. 2 show that our flow approach to this technique is only applicable to those with one of plane components to one direction. However, the results of this approach and the removal of one component of the desired technique are encouraging. The ability to obtain the intensity distribution of the light sheet is a direction in which the velocity gradient and the base of particle due to its plane motion should be regarded to increase the resolution of the measurement. In contrast to conventional PTV, the out-of-plane measurement error of dual-plane PTV can also easily be estimated by analysing the in-plane measurement error.

Fig. 14. Correlation peak height of images of particles (fractional by Gaussian light sheet) (summarised by a spatial averaging of 3 × 3 kernels) for the experiment.

Fig. 15. One-plane velocity distribution obtained by analysing the results of the correlation peaks of $u_{1}$ and $u_{2}$ for each interrogation cell (summarised by a spatial averaging of 3 × 3 kernels for the fine representation).

Fig. 16. Vortex intensity vector map obtained by considering the strongest peak of both correlation $u_{1}$ and $u_{2}$ for each interrogation cell.
Further work is required to improve and verify the accuracy of the technique. High-speed video cameras are already used for PIV in high-speed flows (Hodgkiss et al., 1998), and multiple exposure planes have been used to capture images of particles in sequence at the back of a fourth frame would allow one to capture overall particle motion in position and magnitude direction. The use of dual-plane PIV in motion that of tomographic PIV is merely a modification of the basic technique, in addition to differences in the recording and analysis of the light sheets. Furthermore, only one camera is needed.

This method, even if the accuracy of the technique presented here can be increased, could enable the analysis of multiplanar and multiplano-bifurcated flows, which would increase the accuracy of the method in measurement without increasing the measurement error caused by the perspective projection of the out-of-plane vector components.

Reference

Fig. 16: Three-dimensional representation of the velocity vector of the observed plane (raw data without any smoothing, data validation, or interpolation).