Image Overlapping to Improve Micro PIV Accuracy

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ABSTRACT
Micro PIV uses volume illumination; therefore the velocity measured at the focal plane is a weighted average of the velocities within the measurement volume. The contribution of out-of-focus particles to the PIV correlation can generate significant measurement errors particularly in near wall regions. We present a new application of image overlapping which is shown to very effective in improving measurement accuracy by effectively reducing the measurement depth. The performance of image overlapping and correlation averaging were studied using synthetic and experimental images of micro channel flow, both with and without image pre-processing. The results show that for flows without particle clumping, image overlapping provides the best measurement accuracy without any need for image pre-processing. For flows with particle clumping, image overlapping combined with band-pass filtering provides the best measurement accuracy.

1. INTRODUCTION

Micro particle image velocimetry (micro PIV) is an extension of PIV to measure flows at the micro scale, [5][1]. Due to the small measurement region, it is impossible to create a laser sheet to capture a slice of the flow, as traditionally done in macro PIV. Instead the laser beam illuminates all particles within the viewing volume and both in-focus and out-of-focus particles appear in the image. Thus in micro PIV the depth over which the measurement is taken is the distance over which the particles, both in focus and out-of-focus, significantly affect the measurement. The depth of measurement is characterized by "the depth of correlation" of the imaging system [6][4], where the depth of correlation δz_{corr} is defined as the depth over which the correlation signal of particles significantly contribute to the correlation function. A threshold ε is chosen below which the particles correlation signal is considered negligible, typically ε is 1% of the maximum correlation provided by the in-focus particles [4]). The change of the particles and their correlation signals with respect to the depth or z-direction is illustrated in Figure 1.

The velocity measured in micro PIV is the weighted average of the velocity within the measurement volume, where both the shape and location of the PIV correlation peaks contain contributions from both in-focus and out-of-focus particles. In the majority of cases the contribution from the out-of-focus particles is unwanted. In regions where the contributions of the out-of-focus particles either side of the focal plane are not equal and opposite a bias error results. The implications of this can be demonstrated by considering the channel flow in Figure 1: when the focal plane is at the channel centre all the out-of-focus particles in the PIV image will be travelling slower than the particles at the focal plane and the velocity measured will be lower than the velocity at the channel centre. Similarly, when the focal plane is at the channel wall the micro PIV measurements will overestimate the velocity.

A number of techniques have been developed to improve the accuracy of micro PIV by reducing the effect of out-of-focus particles. Gui et al [1] proposed a band-pass filtering technique to reduce both single pixel random noise and low frequency background noise. By adjusting the filter sizes, band-pass filtering can selectively pass the in-focus particles while suppressing the noise and the out-of-focus particles.

Micro PIV data typically suffers from low seeding densities and low illumination levels and consequently averaging techniques are required. Whilst currently correlation averaging [3], is the method of choice for micro PIV image processing, correlation averaging does not address the errors generated by out of focus particles. The image overlapping technique was originally proposed by Wereley *et al* [6] to increase the seeding density in recorded PIV images. In this paper we propose a new application of image overlapping to reduce the effect of out-of-focus particles.

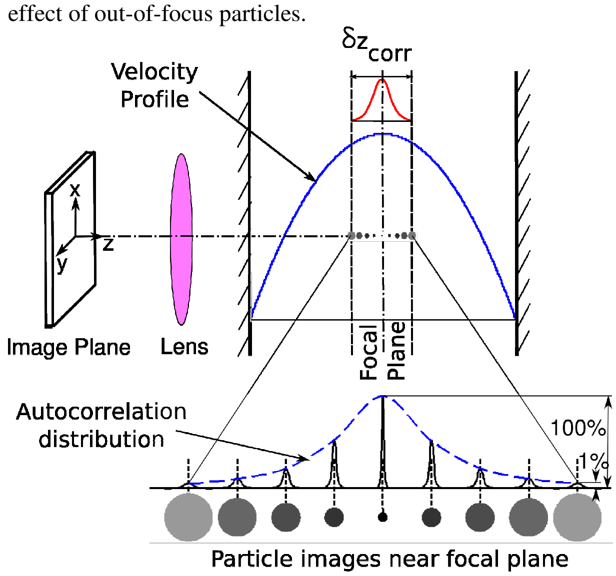

Figure 1. Schematic showing the optical setup for micro PIV of channel flow. The velocity profile is shown as a parabolic curve. The focal plane is located at the centre of the channel. Particles further from the focal plane appear larger and dimmer and the strength of the corresponding peak of auto-correlation decreases. The depth of correlation, δz_{corr}, is defined as the distance over which the peak of the auto-correlation is above 1% of the auto-correlation at the focal plane. Due to the variation of particle correlation signal over δz_{corr}, the measured velocity is a weighted sum of velocity variation within the depth of correlation

2. IMAGE OVERLAPPING TECHNIQUE

Image overlapping is applied to a set of images, I_k by taking the maximum pixel intensity at each pixel location, producing a single overlapped image, I_{max}.:

$$I_{max}(i,j) = max\left(I_k(i,j), k = 1,2,3,\dots N_{pairs}\right) \qquad (1)$$

When applied to a set of micro PIV data consisting of N_{pairs} image pairs, a pair of overlapped images is produced. The first image is derived from the set of N_{pairs} first exposures whilst the second corresponds to the second exposures. Cross correlation is then applied to this overlapped image pair to obtain a time-averaged velocity field As shown in Figure 1, particle intensity varies across the focal plane. The brightest particles are in-focus, close to the microscope focal plane. Further from the focal plane, particles are dimmer and out-of-focus. By collecting maximum pixel intensities, image overlapping collects the brightest particles while excluding dimmer particles at the same pixel locations. In this way image overlapping collects the particles closest to the focal plane, effectively reducing the depth of measurement. Image overlapping requires much less computational time than correlation averaging. In PIV calculations the correlation calculation is the most time-consuming operation. To produce an average velocity vector, image overlapping requires only a single correlation calculation whereas correlation averaging requires N_{pairs} correlation calculations. The time consumed by actual image overlapping, is very small compared to that by image correlation and therefore image overlapping is nearly N_{pairs} times faster than correlation averaging.

Both image overlapping and correlation averaging can be combined with image pre-processing techniques such as band-pass filtering to further improve the measurement accuracy. When applied with correlation averaging band-pass filtering will act to reduce the effect of out-of-focus particles. However, when applied to an overlapped image the main benefit of band-pass filtering is the removal of particle clumps which are often present in experimental data.

3. METHODS

In this paper the performance of image overlapping is compared to that of correlation averaging for measurement of velocity in a micro channel. Results are presented first for synthetic images, where the true velocity is known and subsequently for real experimental data.

3.1 Synthetic Data

A total of 2048 independent image pairs of size 1024 pixels ×1024 pixels were generated in 8-bit greyscale. No artificial noise was added into the images and Brownian motion was not considered. The uniform parabolic displacement profile in *z* direction generates a maximum displacement of 27.03 pixels between image pairs in the channel centre. The velocity in the *x* and *y* directions remains constant. Particles of 1µ*m* diameter are uniformly distributed within the viewing region with particle density of 1.74 x 10^{-4} *particles/µm³*, equivalent to 10,000 particles per image. Particle image formation follows the model employed by Olsen et al [4], with a simulated microscope lens of 10X magnification, 0.30 numerical aperture and 10*mm* working distance. The fluorescent wavelength emitted from the particles is 560*nm*.

To study the effect of varying the number of image pairs (N_{pairs}) used in the overlapping and correlation averaging techniques, an image set containing 2048 pairs was split into 2048/ N_{pairs} image subsets. The measurement techniques were applied to each subset to produce an in-plane velocity field. To make a fair comparison, each result must contain data from the same total number of image pairs, which is 2048. Vector averaging was applied to velocity measurements from the 2048/ N_{pairs} image subsets to provide the final result. When N_{pairs}= 1, the measurement is 100% vector averaging. For PIV processing each image was divided into regions of 64×64 pixels and the velocity calculated within each region. The measured velocity is the average of these velocities. The standard deviation of the measurements was calculated using the velocities for each region for each of the N_{pairs}.subsets.

Results are presented for a measurement plane near the wall, z = 0.9R. This location was chosen instead of z = R as at the wall the correct velocity is zero making it difficult to evaluate the accuracy of the PIV techniques. The results are presented using a normalized measured velocity, $U_w^* = \frac{U_{meas}(z=0.9R)}{U_{theory}(z=0.9R)}$.

3.1 Experimental Method

A syringe pump (Harvard PHD 2000) with a 5cc syringe was used to perfuse glycerol solution through a rectangular channel with a nominal cross section of 2000x200μm^2. The flow rate of 0.02*ml/min* gives a maximum velocity of 1.364*mm/s* at the channel centre, corresponding to a maximum displacement of 19.5 pixels in the recorded images. The glycerol solution was made from a mixture of 2*ml* glycerin, 8*ml* water and 1*ml* fluorescent particle suspension (1% solid). The glycerol solution had density of 1.05 g/cm^3, and viscosity 1.76 centipoise. The Reynolds number based on mean velocity and channel height is 0.11 and therefore the flow can be considered as a Poiseuille flow. The flow was seeded with fluorescent particles, 3µ*m* diameter, density 1.05 g/cm^3 and emission wavelength of 612*nm*. The average particle seeding density in the glycerol solution was 6.43 x 10^{-5} *particles/µm³*.

The refractive index of the glycerol solution causes the 200µ*m* high channel to have an apparent height of 147.06µ*m* when viewed with the objective through air. The channel was displaced relative to the microscope objective using a computer-controlled 3D stage with sub-micron accuracy. The scanning step of 2.5µ*m* generated a 3.4µ*m* displacement of the focal plane inside the glycerol filled channel and 59 steps were required to transverse the channel height.

Images were captured in the centre of the channel width, using a 10× objective lens with *NA*=0.30 and a working distance of 10*mm*. Volume illumination was provided by a continuous diode pumped solid state laser (Melles Griot) emitting at 532*nm* and transmitted to the microscope through a liquid light guide (Leica). A MotionPro X5 intensified camera (IDT) captured 1024 image pairs, 512×512 pixels in size at each scanning location throughout the channel height. To implement the overlapping technique the time between image pairs was selected such that in the slowest regions the particles move more than one particle diameter between image pairs.

For PIV processing each image was divided into regions of 64×64 pixels. The velocities within these regions were averaged to yield the velocity at each z location. Correlation averaging and image overlapping without/with image pre-processing were performed on each data set and velocity measurements are reported in terms of pixel displacements δ*x*. For quantitative comparison between the velocity measurements and the theoretical profile, the norm of the difference, ℓ^2_{norm}, was calculated for each measurement technique, where ℓ^2_{norm} is defined as:

$$\boldsymbol{\ell^2_{norm}} = \sqrt{\sum_{z=-R}^{R}\left(U_{theory}(z) - U_{meas}(z)\right)^2} \qquad (2)$$

4. RESULTS AND DISCUSSION

The effect of increasing N_{pairs} on the measurement accuracy of correlation averaging and image overlapping was investigated using synthetic images. As shown in Figure 2 when N_{pairs} = 1, (the images are processed using 100% vector averaging) the measured velocity is more than 10% greater than the true velocity of U_w^* = 1. With increasing N_{pairs} the measurement using the image overlapping technique (O) converges rapidly to the true result and the standard deviation of the measurement also becomes very small. A similar trend occurs with correlation averaging (Δ) except that the correlation averaging converges towards a value that overestimates the velocity by at least 5%.

Results were also obtained for a measurement plane in the centre of the channel (not shown). Similar trends were found in the centre of the channel except without image overlapping the finite depth of the measurement volume causes the measurements to underestimate the flow velocity.

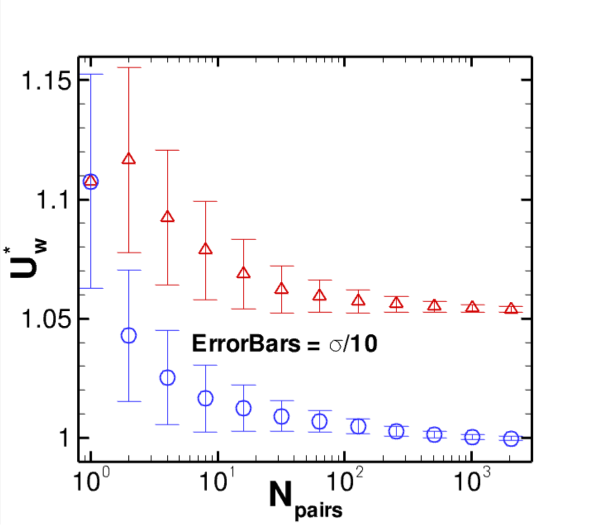

Figure 2. Variation of normalised near wall velocity (z = 0.9R) with the number of image pairs using correlation averaging (Δ) or image overlapping (O). Error bars represent 1/10 of the velocity standard deviation. Velocity measured using image overlapping converges rapidly towards the true value (1) while correlation averaging overestimates the velocity near the wall.

Unlike the synthetic images, the experimental images contain significant noise from various. The particles are of non-uniform diameter, and therefore their brightness is non-uniform. Also in these experiments, particles occasionally adhere to each other forming large and bright particle clumps skewing the velocity measurement towards the velocity of the clumps. As the images with the bright particle clumps will be preferentially collected in the overlapped image the effect of these clumps is greatest on the overlapping technique.

The velocity profile measured in the experimental channel using correlation averaging is shown in Figure 3a. The measured velocity is compared with the theoretical Poiseuille flow showing, as expected, that the measurements underestimate the velocity in the channel centre and overestimate it near wall. The standard deviation of the measurements, represented by the error bars is significant across the flow. The value of ℓ^2_{norm} is a relative measure of the performance compared to the theoretical values averaged over the channel depth.

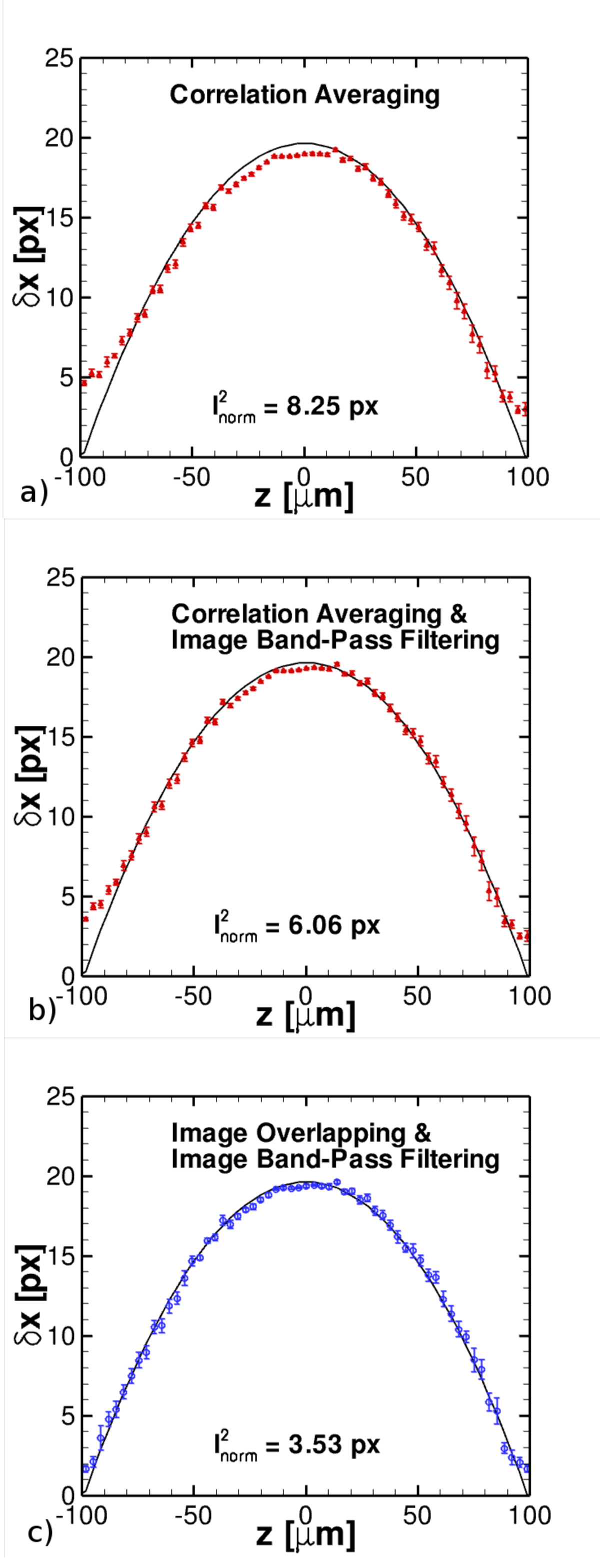

Figure 3. Measured velocity profiles of channel flow obtained with different image processing techniques, error bars represent the standard deviation and solid curves theoretical Poiseuille velocity profile. ℓ^2_{norm} decreases from 8.25*px* with a) correlation averaging only, to 6.06*px* with b) correlation averaging & image band-pass filtering, to 3.53*px* with c) image overlapping & image band-pass filtering. A reduction of 57% in ℓ^2_{norm} is achieved using image overlapping with image pre-processing with the greatest improvement in velocity measurements occurring near the wall.

The performance of correlation averaging can be improved by image pre-processing as shown in Figure 3b. When an optimized band-pass filter is applied prior to correlation averaging, ℓ^2_{norm} drops from 8.25px to 6.06px. The improvements are most significant in the flow centre and near the wall. The use of image thresholding as a pre-processing technique in combination with correlation averaging was also investigated. When the threshold levels were optimized their effect on the accuracy of correlation averaging was similar to that of optimized band-pass filtering with ℓ^2_{norm} = 6.79px.

The most accurate measurements were obtained using image overlapping with an image band-pass filter. This method produces excellent results as shown in Figure 3c. The ℓ^2_{norm} value of 3.53 is almost half that of correlation averaging with optimum image processing. In particular accuracy is significantly improved in the near wall region where the velocity gradients are greatest.

The application of image band-pass filter as a pre-processing technique was found to successfully remove particle clumps from the overlapped images. Image pre-processing was only necessary in images with particle clumps. Image thresholding prior to overlapping does not remove the particle clumps and was found to produce little improvement in accuracy. This result shows that even in images with particle clumps with appropriate pre-processing, image overlapping can produce significantly better measurement accuracy than correlation averaging.

5. CONCLUSIONS

The velocities measured using micro PIV are biased by the velocities of out-of-focus particles. The application of image overlapping to reduce the depth of measurement can significantly reduce these errors. This was illustrated using channel flow where compared to standard correlation averaging, image overlapping produced a 57% reduction in the value of ℓ^2_{norm}. The improvements in measurement accuracy were greatest in the near wall regions.

Image overlapping is performed by taking maximal intensities from an image set to produce a single overlapped image. PIV correlation is applied only once on a pair of overlapped images to produce an average velocity measurement. As the in-focus particles are brightest, they are accumulated in the overlapped image. As a result, the measurement using overlapped image pair provides the velocity of particles close to the focal plane. This effectively reduces the depth of measurement and the associated errors. Experimental images containing clumps of particles may require image pre-processing to remove these clumps before image overlapping can be effective.

Correlation averaging has for the past decade been the gold standard in micro PIV processing. However, using both synthetic and experimental images image overlapping was shown to out-perform correlation averaging particularly in the near wall region. For synthetic images without particle clumps, with sufficient image pairs the velocity measured in the near wall region using overlapping converged to the true velocity, whereas correlation averaging significantly overestimated the velocity. For experimental images containing particle clumps, the measurements using image overlapping without pre-processing suffer bias errors from the clumps. With the application of band-pass filtering to remove the clumps, image overlapping continues to produce the best measurement accuracy. Image overlapping with band-pass filtering reduces by 57% the measurement errors compared to that of plain correlation averaging, and by 42% the measurement errors compared to that of correlation averaging with band-pass filtering

In summary, image overlapping produces significantly improved measurement accuracy with significantly less computational effort than correlation averaging. This simple algorithm reduces the depth of measurement, producing significant improvements in accuracy in regions where measurements would otherwise be biased by the velocities of out-of-focus particles. Image overlapping presents an opportunity to easily improve measurement accuracy in the critical wall region and thus is particularly relevant to biological flows.

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