A Novel Technique to Improve Near Wall Resolution in PIV using Cylindrical Lenses: DMPIV

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Abstract

Instantaneous planar velocity field measurement techniques are now common tools used in fluid mechanics research and applications. Particle Image Velocimetry (PIV) is perhaps the most common among these techniques that are currently being used to measure such instantaneous flow fields. However, most planar measurement techniques, including PIV, suffer from the drawback that reliability is compromised in domains that include interfaces and boundaries. Near wall measurements in PIV are often very difficult and characterized by large errors and uncertainties because of difficulties encountered with scattering of light from wall boundaries and lack of seed particles near the wall. In addition, velocity gradients are often very large close to the wall so resolution and accuracy is compromised in the wall normal direction.

We propose a novel technique to improve the resolution and quality of data obtained close to a wall or an interface. In the technique, flow is magnified selectively in one direction while the original field of view, in the perpendicular direction, is maintained. This directional magnification is obtained by using a cylindrical lens of short focal length which causes the seed particles to appear elongated and distorted – i.e. streaky - in the direction of magnification. The major challenge in this approach is to identify and account for individual particles that are elongated directionally and to process these images into accurate velocity fields. The images are pre-processed to replace the stretched particles with point particles before being processed using standard PIV algorithms. This paper demonstrates the successful use of cylindrical lenses for directional magnification of static targets and flows seeded with particles, along with some preliminary results obtained from processing these images. Several problem issues encountered are also discussed and possible solutions noted.
1. Introduction:

Optical flow diagnostic techniques are fast becoming the mainstay of fluid mechanics measurements with the rapid advances in lasers, instrumentation and computer technology. Particle Image Velocimetry (PIV) is a technique that benefits considerably from these advances in technology. The basis for PIV was laid down by Adrian (1985) with his analysis of auto-correlation of double exposure PIV images. This was further developed and generalized for application to multiple exposure images and cross correlation analysis of highly resolved PIV photographs (Keane and Adrian, 1992). With advances in technology, the technique was adapted for use with electronic cameras and digital PIV images with the development of methods to estimate the displacements at the sub pixel level (Willert and Gharib, 1991). PIV thus became a powerful and standard tool to study fluid flows in a lab setting. However, standard techniques perform poorly in some regions of flows with high velocity gradients. In the case of flows close to stationary walls, the problem is doubly compounded by the lack of particles to scatter light in the near wall regions and the contamination of the image by the reflection and scattering of the incident laser light by the wall itself.

This paper describes a new technique which we shall call Directionally Magnified PIV (DMPIV) to enhance the resolution of PIV images in one direction while maintaining the resolution in the second dimension. This directional magnification is achieved using cylindrical lenses of short focal length and a single camera. The technique is first applied to a static target – a grid, to study the directional magnifications possible. The technique is then applied to simple flows and the results compared with those without directional magnification. Due to the directional magnification, the seed particles in the flow are stretched in that direction and appear like streaks. The streaky images are processed to obtain images that can be processed with standard PIV processing techniques to obtain velocity information. Issues associated with imaging and processing of flow fields using this technique are also described and discussed.

2. Experiments and results

Image acquisition set up:

For all images, a CCD camera with 1024 x 1280 pixels and 12 bit resolution is used with standard Nikkor lenses. The camera is placed at right angle to the target which is illuminated using a studio light in the case of a static target and a dual cavity, pulsed Nd:YAG laser in the case of fluid flow. The images are acquired directly to a computer and stored as 16 bit TIFF images to preserve as much image information as possible.

a. Static target:

A static target is used to assess the directional magnifications achievable for the various cylindrical lenses used. The main criteria for the choice of the target were that it should be a satisfactory target for use with cylindrical lenses of various focal lengths and sizes to study the selective magnifications possible, and also be useful to assess the variation of the image quality away from the center of the image. With these ideas in mind, a metric grid of size 10mm x 10mm was chosen as the target of choice. The target was mounted on a metal block to give high contrast between the grid and the background. The resulting images are shown in figure 1. All images are obtained with a 105mm lens operated at f8 mounted on the CCD camera. The target with no directional magnification as shown in fig. 1a shows the metric grid with a fiducial mark to orient and identify the region being imaged. Figures 1b, 1c and 1d show the target grid imaged with cylindrical lenses of focal length 75.6mm, 38.1mm and 25.4mm respectively. The directional magnification increases, as expected, with decreasing choice of focal length of the cylindrical lens. Using a lens of focal length 75.6mm, the magnification is about 1.5 in the vertical direction and 1 in the horizontal direction. A vertical magnification of 2 is obtained using the shortest focal length of 25.4mm. In all the directionally magnified images, the image quality worsens as the distance from the center of the image increases. The horizontal lines on the target are ‘smear ed’ out more towards the top and bottom edge of the image – these line edges are not sharply defined in the digital images as in the case of the unmagnified image. The thickness of the horizontal lines increases with increasing magnification and with distance from the center of the image. The resolution and quality of the images remains good in the non-magnified direction, i.e., the horizontal direction. The fiducial mark is stretched in the direction of magnification and the edges of the mark are less clearly defined.

These results suggest that it is possible to selectively magnify the field of view in one direction, i.e. to effectively improve the resolution in that direction while keeping the resolution in the perpendicular direction unchanged. The results obtained from the static target imply that on application of the directional magnification technique to image flow fields for PIV, the particles would be stretched in one direction and edges of these stretched particles would be smeared out. Additional processing of these stretched particle images would likely be needed before they can be used with standard PIV algorithms to obtain velocity data.
b. Fluid flow:

To test the usefulness and applicability of the directional magnification technique, a simple proof-of-concept experiment was set up to study the particle stretching and obtain test images of directionally magnified flows to examine the image processing algorithms. A square container was filled with water and stirred to give the fluid a counter clockwise swirl. A schematic of the test setup is shown in figure 2. The regions of flow imaged with and without the directional magnification are indicated in figure 2b with the cross-hatched region and the region bound by the dotted line. Sample images obtained in this experiment are shown in figure 3. A flow image of size 17 mm x 14mm obtained in the region adjacent to the wall as shown in the schematic without the use of the cylindrical lens for directional magnification is shown in figure 3a. The result of processing this PIV image is shown in figure 4a. The flow is uniform and follows the streamlines that are expected in a swirling flow in the region imaged. Figure 3b shows a sample PIV image with directional magnification obtained using a cylindrical lens placed in the light path. The image corresponds to a region 7mm x 14mm closest to the wall in the test setup and is indicated by the cross hatched region in the schematic shown in figure 2. The seed particles are stretched in the horizontal direction and appear as streaks because of the directional magnification in that direction by the cylindrical lens. The particle edges are also less well defined in the horizontal direction with the intensity at the ends of the particles being spread over more pixels than in the image with no directional magnification.

To process the images with the stretched particles, an algorithm was designed to replace the streaks with finite sized particles. A minimum intensity is chosen for each image based on the average intensity across all the 1024 x 1280 pixels in the image. A set of particles is then marked as a streak if the intensity of a continuous row of pixels is higher than this minimum intensity. A check is also made of the adjoining rows to ensure proper identification of the particle streaks. Once a streak is identified, its centroid is calculated and the streak replaced by a 3x3 circular particle with a Gaussian intensity distribution. The modified image with this simulated distribution of particles is then processed using standard techniques applied to PIV images.

Figure 4b shows the result of processing an image similar to one shown in fig 3b. The vector plot shows a marked improvement in the resolution of the flow close to the wall. The gross flow is resolved correctly over most of the image except in regions where the relative fluid motion is small. The direction and magnitude of the fluid velocity is predicted correctly over most of the imaged area. The gradient in velocity close to the wall is seen to be magnified and better resolved. The vectors closest to the wall have the lowest magnitude of velocity as expected. However, the vector plot also shows some obvious errors in the flow field. The flow in some regions is also not in the expected direction. Some regions of the flow are also uniform in direction and magnitude. These issues are further discussed in the issues section below.

The directionally magnified PIV technique was then applied to a large-scale flow – a Newtonian turbulent boundary layer. The boundary layer facility and the flow are described in detail in White et. al (2004). The optical setup on this facility is shown in figure 5. The cylindrical lens cannot be directly focused on the flow in this set up because of the lens’ short focal length. On the boundary layer tunnel, a spherical lens was used instead to image the laser sheet to a focal plane outside the tunnel. A cylindrical lens – spherical lens system is then used to directionally magnify the flow. Figure 6a shows a sample image obtained with this setup close to the wall using this telescope-like arrangement of lenses without the cylindrical lens. The imaged area is 37mm x 29.5 mm in size. The center of the image is well focused and individual particles are identifiable. The outer regions of the image are, however, distorted because of the finite size of the lenses and the short distance between the camera and the lens system. The directional magnification is obtained by placing a short-focus cylindrical lens in between the spherical lenses. A sample image obtained with this setup is shown in figure 6b. With directional magnification, the physical size of the region imaged is 37mm x 20.8mm, i.e a magnification ratio of 1.4. The particles in the central focused region of the image are stretched in the vertical direction and appear as streaks similar to those seen in the experiment above. These images are processed using the image processing algorithm described above which replaces the streaks with particles at appropriate locations before they are processed with standard PIV algorithms. The final processed vectors, averaged over 5 images, from the unmagnified and magnified images are shown in figures 7a and 7b respectively. The noise associated with the displacements in the vertical direction is due to the error in locating the correct position on the particle streak and replacing it with a point particle. This error increases as the distance from the center of the image increases, as was seen in the static images. The mean magnitude of the velocity is well predicted in the horizontal direction.

3. Issues:

a. Optical issues:

The use of cylindrical lenses for directionally magnifying the flow field is limited by several optical issues. The foremost of these issues is the blurring of the images because of the extreme thickness of the short focal length cylindrical lenses made of glass. Because of the thickness, it is extremely difficult to get a sharp focus in a lens
system using a short focus cylindrical lens. This effect can be minimized with the use of lenses made of material with high refractive indices which would enable the thickness of the lens to be reduced. It has been suggested (Oweis and Ceccio, 2004) that prisms can also be used to obtain directional magnification. The use of prisms may eliminate effects due to the curvature of glass lenses and the resulting image may be more uniform spatially. Alternately, use of a known target can lead to a distortion pattern being acquired which can subsequently be used to renormalize the particle images and thus correct for distortion.

b. Processing issues:

Processing the directionally magnified PIV images involves identification of the particles, which are imaged as streaks, and replacing these streaks with point-like particles that can be handled by standard PIV algorithms. The algorithm described above identifies and replaces the streaky particles with point-like particles at the centroid of the streak. The algorithm works on the image itself and the search and replace algorithm is quite time consuming. The algorithm also has problems identifying overlapping or near-overlapping particle streaks. For example, if two particles streak overlap, the algorithm replaces them with a single particle at the centroid of the overlapping particle streaks. This leads to significant loss in particle density and image quality. These images are initially divided into 128 x 128 pixel interrogation regions and, in the next iteration, the interrogation region is reduced to 64 x 64 pixels. The particle density for interrogation regions below this size is very low and the vectors obtained have large errors associated with them. This problem becomes worse as the magnification is increased. With a magnification of 1.4, in the images obtained in the large scale flow experiment, the errors in the vertical direction are noticeable, but can be averaged out using a large number of images. With higher magnifications, the errors are much larger and the image quality significantly worse.

A centroid fit is used on the particle streak intensity to locate the position of the point particle and this method produces errors as shown by the noisy results obtained from the PIV vectors. The problems associated with this technique are similar to those associated with the subpixel resolution of PIV vectors. Westerweel (1997) has shown that for subpixel interpolation, a Gaussian peak fit works better than a centroid fit to the intensity data. The same idea could be used in the replacement of the streaky particles by fitting a Gaussian to the intensity of the streak and obtaining the peak location. An iterative multigrid method utilizing discrete window displacements similar to the technique described by Scarano and Riethmuller (1999), has been implemented and tested on the images obtained in the experiments above. The incorrect prediction of the magnitude and direction of the vectors observed in some regions of the flow in figure 3b are due to incorrect biasing of the iterative scheme used in the technique. The results show some qualitative improvement and the technique needs to be further fine tuned and tested to be effective.

4. Closing remarks:

A technique to selectively improve the resolution of PIV in a particular direction while maintaining the spatial resolution in the perpendicular direction and using a single camera, is demonstrated. The use of a cylindrical lens to obtain direction magnification in one direction causes the point particles to be stretched and appear as streaks in the particle images. The processing technique of these images to replace the streaks with point particles at the appropriate locations is the most important issue that has to be carefully addressed in order for the technique to be successful. The present technique of using a centroid fit causes loss in particle density and image quality and hence needs to be improved. An autocorrelation based technique to do this is being studied at present. The use of DMPIV in conjunction with other techniques like image parity exchange (Tsuei and Savas, 2000) will eventually go a long way in improving the resolution of data close to walls and interfaces.

References:
Figure 1: Images of static target grid obtained (a) without cylindrical lens, (b) with 75.6mm focal length cylindrical lens, (c) with 38.1mm focal length cylindrical lens and (d) with 25.4mm focal length cylindrical lens.

Figure 2: Schematics showing (a) side view of test setup and (b) flow, laser light sheet and areas of flow imaged with different lenses.
Figure 3: Images obtained in a swirling flow using (a) no cylindrical lens and (b) with cylindrical lens showing particle stretch in the horizontal direction.
Figure 4: PIV vector plots obtained by processing image pairs similar to those shown in fig. 3. (a) Vector plots with no directional magnification and (b) vector plots with directional magnification achieved using a cylindrical lens.
Figure 5: Schematic showing boundary layer water tunnel cross section and optical setup for directional magnification
Figure 6: Images taken in the boundary layer facility: (a) with no cylindrical lens, close to the flat plate and (b) with directional magnification achieved using a cylindrical lens close to the flat plate.
Figure 7: Vectors plots obtained by processing image pairs similar to those shown in Fig 6. (a) shows an average over 5 vector plots for the case with no directional magnification. (b) shows an average of 5 vector plots of the directionally magnified flow images.