RECONSTRUCTION OF VECTOR FIELD IN FLUID MEASUREMENT

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ABSTRACT

A new approach of image processing is proposed to enhance the spatial resolution of fluid flow field measurement. The local estimate velocity is first found in a sub-image region. The particles in the region are then located individually. The corresponding particles are matched by using the estimate velocity and the particle locations in conjunction, making it possible to produce more velocity measurements from the smallest PIV measurement sub-region. The proposed method has been proved successful by testing the experimental result from Urushihara et. al. [6]

1. INTRODUCTION TO PIV

Particle-image velocimetry, or PIV, is a particle-imaging technique that measures the motion of illuminated regions of a fluid by observing at two or more times, the locations of tracer particles which follow the fluid flow [1]. A typical planar PIV system is shown in Fig. 1. A pulsed light sheet illuminates the particles in the fluid. The particles scatter light onto a photographic lens which is perpendicular to the sheet, and images are captured on film or on video. The size of a PIV photograph typically is $100 \times 125\ mm^2$. Then, frame grabber digitizes the image and transfers the data to computer for analysis. The process of analysis is also known as "interrogation." The interrogation process divides the digitized PIV photograph into many small images, called "interrogation spots," each about $1mm^2$, containing 20-30 particles. The interrogation spot is analyzed with correlation analysis as described below to give the average velocity vector. By repeating this process, a whole frame of PIV images can be investigated and a velocity field obtained. The auto-correlation of the interrogation spot is computed as,

$$R(\vec{s}) = \int I(\vec{x})I(\vec{x}+\vec{s})d\vec{x} \qquad (1)$$

where $I(\vec{x})$ is the interrogation spot image, and $\vec{s}$ is a displacement vector. The particle displacement $\vec{s_o}$ is measured from the central self-correlation peak to the second peak. Then, the average velocity $\vec{u}$ inside this small region is calculated from,

$$\vec{u} = \vec{s_o}/\delta t \qquad (2)$$

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where δt is the time interval between light pulses, and $\vec{s_o}$ is the correlation peak vector from the PIV sub-image analysis. The performance of a PIV system is defined by the spatial resolution, detection rate, and accuracy. To obtain accurate velocity measurements for a range of flow fields on as fine a spatial scale as possible, it is desirable to improve the spatial resolution of PIV without sacrificing the accuracy of the measurements. H. T. Huang et. al. uses an image warping method to incorporate velocity gradient into the interrogation process to improve PIV performance in the high velocity gradient region [4] [5]. This paper introduces an alternative method which uses sub-interrogation particle tracking.

2. COMBINED METHOD TO IMPROVE PIV

To obtain a valid correlation result, i.e., to successfully locate the second correlation peak without finding a noisy correlation peak, there should be at least 6-8 particles inside an interrogation spot [2]. Thus, the locations of these particles can be tracked and corresponding particle pairs can be matched, such that more velocity vectors can be found in this small region. The proposed method consists of five steps:

2.1. Find the Local Average Displacement Vectors

A regular image analysis (correlation) is performed to find the averaged velocity vector of each interrogation spot. In order to find the best local velocity estimate value, a cross-correlation method is used instead of the auto-correlation method. The cross-correlation method uses two small sub-image regions to do the correlation computation, which has been proven to have better performance in finding the signal correlation peaks than that of the auto-correlation method [2]. When the average local displacement and time interval δt are known, the mean velocity inside an interrogation spot can be computed as,

$$\delta\vec{x} = M\vec{u}(\vec{x},t)\delta t \qquad (3)$$

where M is the magnification of the PIV system, $\vec{u}(\vec{x},t)$ is the average velocity from PIV interrogation and δt is the time interval between light pulses.

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2.2. Find the Particle Locations

Particles are found and their centroids are computed for each interrogation spot. The PIV photograph is first binarized with a preset threshold gray level, i.e., if the gray level of a pixel is greater than the threshold value, it is set to 255, otherwise it is set to 0. Then, the correlation subimage in the PIV analysis is scanned to detect the possible particles. Normally, particles in the PIV photograph are seen as groups of pixels with similar properties (gray level) that distinguish themselves from the background. The scan procedure is as follows: first, the image is inspected column by column. If neighboring pixels both have the same gray level of 255, they are set to the same pixel group by assigning a group label to these pixels. After the whole column is scanned, the process continues with the next column. After the second column scan is finished, the groups which connect to each other are merged and are assigned a new group label. This process repeats column by column, until the whole image is completed. Then, the size of every group is computed. When the size (or area) of a group is greater than a predetermined average particle size, it is considered to be a particle. The particle centroid is calculated and stored to indicate the particle location in the image.

2.3. Matching the Corresponding Particles

Unlike normal motion compensation in digital image processing where the actual motion is not known a priori, we do know where the particle moves in the next instant. Hence, we are more able to develop a particle correspondence. The guide line comes from the regular PIV analysis which produces an initial estimation of the particle local displacement. Also, from these particle locations, reasonable particle pairs can be found by starting from one particle and looking for the second particle in a small, circular region around the predicted position of the second particle, as shown in Fig. 2. If there is a particle encircled in the searching range, a correspondence is found. If two correspondences are found for a single particle, one is considered spurious and is rejected. A correspondence is not found if the particle moves out of the sub-region. This can be resolved by enlarging the range of the searching area. A raw velocity field can be calculated from equation (3).

2.4. Cleanup the Vector Field

Outliers are caused by two major sources, the tracking of particle locations, and the matching the corresponding particle pairs. Although the number of outliers in the measurement is not very large, their effect on the interpolation of the vector field may not be inconsequential [7]. Therefore, outliers in the raw velocity field should be picked out before the interpolation is done. A local mean filter is used to eliminate the outliers. First, an averaged reference velocity is computed for the region surrounding the target velocity vector. Next, the target vector is compared to the reference vector. If this target velocity is outside a certain region of the reference velocity, it is considered an outlier.

2.5. Obtain Vector Field on Regular Grid from Interpolation

Since the velocity vector field from particle tracking analysis is a randomly located vector field, it is desired to have the velocity information on regular grid points. Previous work has shown the application of interpolation using the multivariate reciprocal quadratics method [8], the adaptive gaussian window method [3] and the one-step robust method [7]. An adaptive gaussian window (AGW) interpolation method is used to compute the velocity at regular grid points [3].

$$\hat{u}(\vec{x}) = \frac{\sum_i w(\vec{x} - \vec{x_i})\vec{u}(\vec{x_i})}{\sum_i w(\vec{x} - \vec{x_i})} \qquad (4)$$

where $w(\vec{x} - \vec{x_i})$ is a gaussian weighting funciton, $\vec{u}(x_i)$ is the velocity at random locations, and $\hat{u}(\vec{x})$ is the velocity at a regular grid point.

3. EXPERIMENTAL RESULTS

To test the feasiblility of the proposed method, turbulent pipe flow data was re-analyzed [6]. This 2D PIV result resolved turbulent eddies down to 244 μm in the fluid boundary layer. Images of small regions of interest in the double-pulsed photo were selected to illustate the enhancement of spatial resolution. These regions are outlined in Fig. 3, and contain flows with high local variations in the velocity field. Region A had a strong shear flow. The velocity in region A changed sharply, causing the correlation peak searching algorithm to fail at some locations when locating the second correlation peak. Using our new method, we expected a better result. The regular PIV analysis was performed on a TSI-6000 system, which included a CID camera, a DT-2861 frame grabber, a Mercury array processor, and a PC-386 Dell computer. Region A occupied $3.3 \times 3.3mm^2$ in the real flow field. PIV analysis gave a 20×20 grid point resolution velocity field, as shown in Fig.3. Particle tracking was implemented in region A, identifying 9322 particles with 23 particles for every interrogation spot. An estimated velocity field was obtained by matching 3295 particle pairs out of 4661, as shown in Fig. 5. After using a local mean filter to pick out outliers, 2363 vectors were accepted out of 3295 in Fig. 6. AGW was implemented to compute the velocity on the regular grid points as shown in Fig. 7. The resulting in 2500 vector measurements were 6 times greater in number more than the PIV result. The detailed velocity variations in the center part region A can be seen clearly. Similar results were obtained for regions B and C.

4. CONCLUSION

A new approach to improving fluid flow field measurement to a higher spatial resolution is presented. This method combines the conventional high image density correlation technique (PIV) and the low image density tracking technique (Particle tracking technique). It provides a way to measure high velocity gradient flow regions.

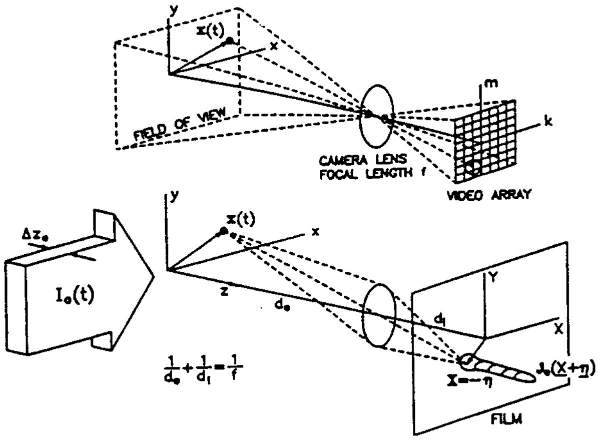

Figure 1: Optical system of a planar particle-image velocimeter. (Top) Video recording; (Bottom) Photographic recording [1].

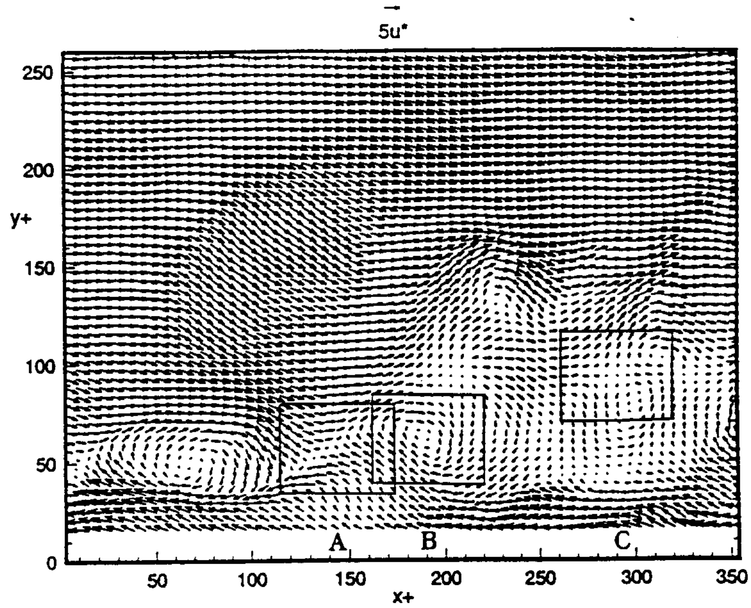

Figure 3: PIV measurement of pipe flow of in-plane velocity vectors [6].

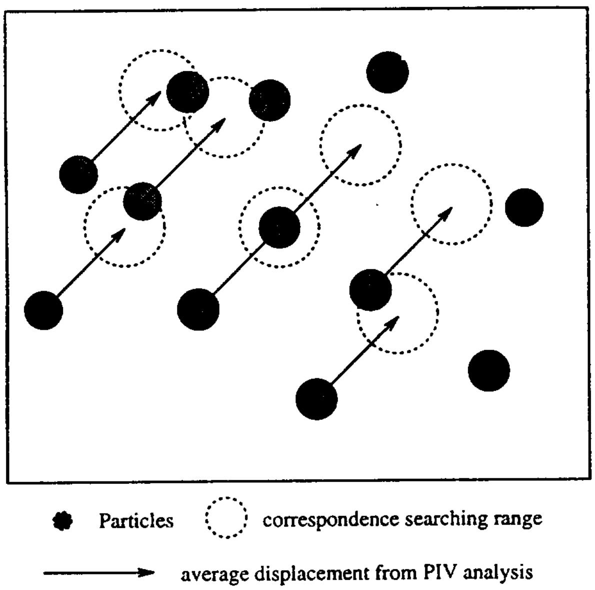

Figure 2: Finding correspondence particle image pairs.

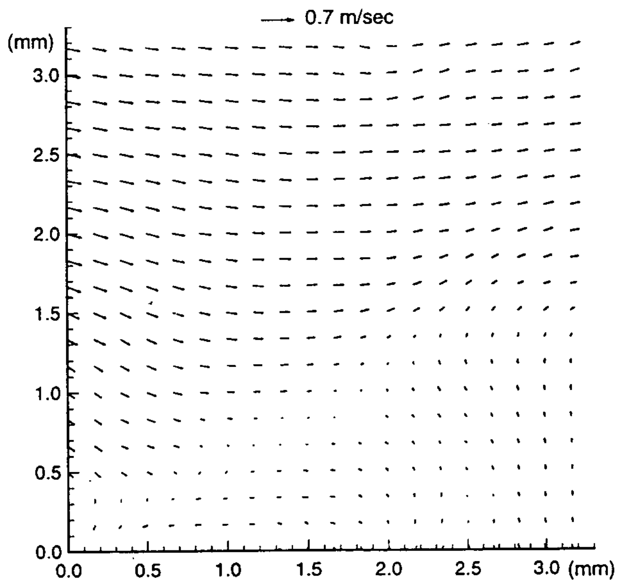

Figure 4: smoothed PIV vector field 20x20 vectors, obtained from TSI-6000 system.

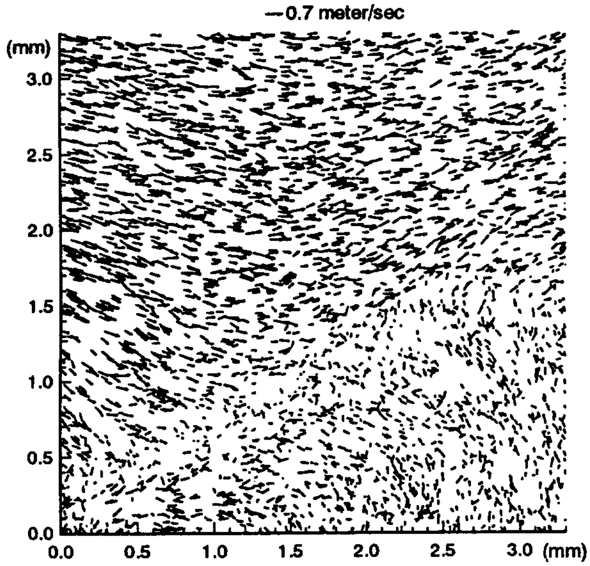

Figure 5: Raw PTV vector field, obtained from combined PIV and PTV result, 3295 vectors are found out of 4661 possible particle pairs.

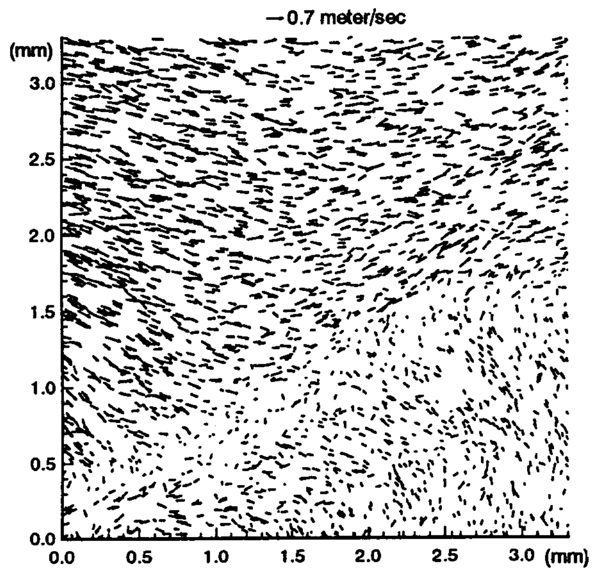

Figure 6: smoothed velocity field, using local mean filter to remove the outliers, 2363 velocity vectors accepted out of 3295.

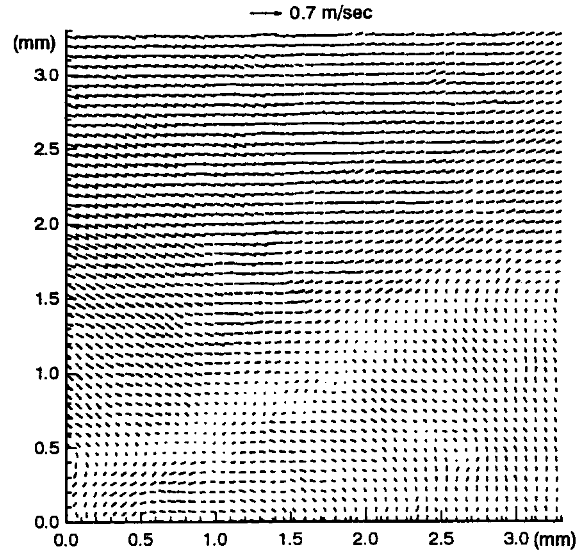

Figure 7: enhanced spatial resolution velocity field with 50x50 vectors, after AGW interpolation.

5. REFERENCES

[1] R. J. Adrian, "Particle-imaging techniques for experimental fluid mechanics", *Ann.Rev.Fluid Mech*, Vol.23, pp. 261-304, 1991.

[2] R.D. Keane and R. J. Adrian, "Optimization of particle iamge velocimeters, Part I:Double-pulsed systems", *Meas.Sci.Technol*, pp. 1202-1215, 1990.

[3] J. C. Agui and J. Jimenez, "On the performance of particle tracking", *J. Fluid Mech*, Vol. 185, pp. 447-468, 1987.

[4] H. T. Huang et.al., "Limitation and improvement of PIV, Part I: Limitation of conventional techniques due to deformation of particle image patterns", *Exp.Fluids*, 15, pp. 168-174, 1993a.

[5] H. T. Huang et.al., "Limitation and improvement of PIV, Part II:Particle image distortion, a novel technique", *Exp.Fluids*, 15, pp. 263-273, 1993b.

[6] T. Urushihara et.al., "Investigation of the logarithmic layer in pipe flow using particle image velocimetry", *Elsevier Science*, 1993.

[7] Jialin Zhong, Juyang Weng, Thomas S. Huang. "Vector field interpolation using robust statistics", *SPIE Conf. on Curves and surfaces in Computer Vision and Graphics II, Boston*, pp. 58-67, 1991.

[8] D.J.Koga, "An interpolation scheme for randomly-spaced sparse velocity data", *Technical Report of Stanford University*,1986.