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Construction of Virtual Images for a Benchmark Test of 3D-PTV Algorithms for Flows

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Abstract : Virtual images for PIV are produced for the construction of a benchmark test tool of PTV systems. Camera parameters obtained by an actual experiment are used to construct the virtual images. LES(Large Eddy Simulation) data sets of a channel flow are used for generation of the virtual images. Using the virtual images and the camera's parameters, three-dimensional velocity vectors are obtained for a channel flow. The capabilities of a 3D-PTV algorithm are investigated by comparing the results obtained by the virtual images and those by an actual measurement for the channel flow.

Key words : Virtual image, 3D-PTV, Benchmark test, Channel flow

1. Introduction

Particle Imaging Velocimetry (PIV)[1] is capable of measuring the whole flow fields two-dimensionally or three-dimensionally without disturbing the flow field, which has been impossible for the conventional measurement technique such as, Probes, Hot-wires, and LDV. The whole field measurement is of great importance in investigating the flow structures. However, there have been no standard evaluation tools for investigating the capabilities of these PIVs, which made PIV techniques still remained far from popularization or generalization. A lot of PIV techniques had been developed and applied to various flow fields. The techniques include cross- correlation technique[2][3][4], four-step particle tracking technique[5], two-step particle tracking technique[6], and so on. The developers analyzed the effectiveness of their PIV techniques using their own evaluation methods. Since there are no standard evaluation tools for investigating these PIV techniques, no standard PTV technique

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exists and most of the researchers arbitrary choose PIV technique without any consistency in using various PIV techniques to their experiments. Even if they could get the velocity distribution using a certain PIV technique, there were also no standard evaluation tools for the measured data. Every researcher had not only to evaluate his PIV data with his own way to get the accuracy of the measured data, but also to overcome many complicated experimental procedures such as, fabrication of test section, visualization, image capturing, image analysis, particle tracking. These facts made many researchers working in the field of fluid engineering not to be intimate with the PIV techniques. To popularize the PIV technique for practical use, the PIV standards and the PIV guide tools should be settled. Gharib et al[7]. proposed a PIV standard images for evaluation of the DPIV(Digital PIV) technique. They distributed the PIV images for the Rankine vortex function and the shear layer function. The images were constructed from the two-dimensional velocity distribution without imbedding any noise into the images. Three-dimensional motion and image noise was neglected in the study. Okamoto et al[8]. proposed a PIV standard project (PIV- STD3D) and constructed a PIV standard images on a website (http://www.vsj.or.jp/piv) considering the three-dimensional motion of a jet flow. However, interior parameters of camera such as, focal length and distortion of lens, deviation of the principal point from the center of image were neglected. In order to make a benchmark test of our 1-Frame 3D PTV algorithm[9] considering the whole elements that affect the final accuracy of three-dimensional measurement, a virtual image set is generated individually using an LES data sets of a channel flow. Further, an evaluation of the 1-Frame 3D-PTV algorithm is made through an actual measurement experiment.

2. Virtual Images for Benchmark Test

2.1 Requirements of the virtual images for benchmark test

The objective of generation of PIV virtual images is to construct an evaluation tool for PIV techniques. The least requirements[8] to be considered for the generation of the virtual images for benchmark test are as follows. 1) PIV Image Configurations such as, density of particles, concentration of particles, velocity, velocity gradient, laser sheet thickness and so on. The PIV images should be designed considering these parameters. 2) Reproducibility for Actual Flow Field such as, transient flows and three-dimensional flows. Since identification of the particles′ positions is one of the most important process, location and orientation of camera, and magnification should be considered. And the refraction at the vessel wall should also be taken into account since the actual flow fields are inside the vessel. 3) Reliable Data Set for Evaluation. In order to check the capability of each PIV technique, reliable data set should be provided for comparison. 4) Easy Accessibility of the Constructed Virtual Images for worldwide test. In this study, a set of virtual images is generated for an evaluation of our 3D-PTV algorithm mainly considering the above requirements.

2.2 Generation of flow field

In this study, the velocity vectors obtained by LES for a channel flow are used for the generation of virtual image particles. Fig. 1 shows schematic view of virtual flow field of a channel flow. Reynolds number, $Re_T(u_T\delta/v)$, is 180, where u_T is the friction velocity and δ is the half height of the channel. The simulation volume is 3.2H x 1.0H x 1.6H for x, y, z-directions, where H is 100 mm length.

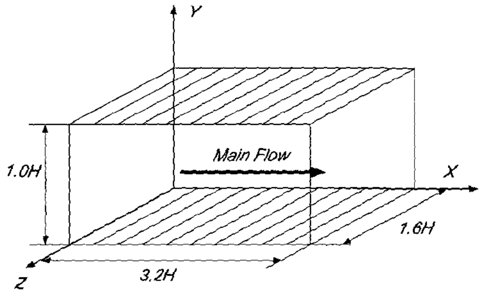


Fig. 1 Schematic of the target flow field.

The volume is divided into 64 x 32 x 32 meshes. Instantaneous three-dimensional velocity distributions in a certain test volume are extracted from the simulation results with every 15 msec. The particle movement in the image is calculated using the extracted instantaneous three-dimensional velocity vectors. Fig. 2 shows an example of the instantaneous three-dimensional velocity distribution of the simulated flow field. The number of vectors on the meshes was reduced to 8,192 purposely to make easy view.

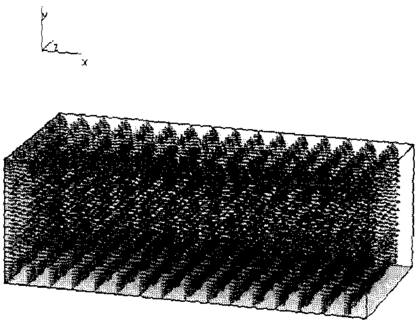


Fig. 2 Instantaneous 3D velocity distribution obtained by LES.

2.3 Virtual image generation

The absolute coordinate system (x, y, z) is defined as shown in Fig. 1. The particle positions of the photographic coordinate system are obtained by transforming the absolute coordinate system into the camera coordinate system considering the camera location and orientation vector.

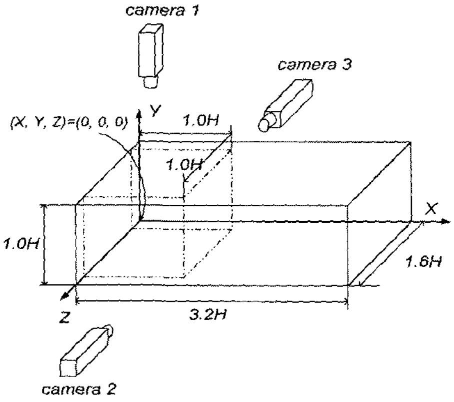


Fig. 3 Camera arrangement for virtual image generation.

The cameras were virtually arranged in order to simplify the procedure of the benchmark test of 3D-PTV algorithms as shown in Fig. 3 for a channel flow. The size of generated image is 512 x 512 pixel. Each pixel has 256 gray levels (8bit). The images of particles are generated on the image of each camera. The intensity at the location (X, Y) in the image caused by the scattered light from the particle (x_p, y_p, z_p), whose projection is (X_p, Y_p), is expressed as equation (1).

$$I(X,Y) = I_0 \exp\left(\frac{(X - X_p)^2 - (Y - Y_p)^2}{-(d_p/2)^2} \right) \tag{1}$$

In order to emulate the laser illumination, the maximum intensity (I_0) is defined as the equation (2) considering the particles' locations. The light is assumed to be parallel and cylindrical illumination toward the measurement target.

$$I_0 = 240\left(-\frac{z_p^{\,2} + x_p^{\,2}}{\sigma_l^{\,2}} \right) \tag{2}$$

Here, σ_l is the radius of the cylindrical light. As an initial condition, the particles are randomly generated in a certain volume. The diameters of particle are also determined with a random generator considering the average and standard deviation of the diameter. Then the initial image is generated using the above equations. The particle movement is calculated from the LES velocity data with every 15 msec. Since the particles' three-dimensional locations are known with time, the three-dimensional velocity vectors at a certain points are calculated using the linear interpolation of the LES data. The particles' locations are shifted to make virtual locations of particles in the next image. Then the new image at the next time step is generated using Eqs. (1) and (2). This procedure is repeated for certain periods. With increasing the number of particles, the number of overlapped particles is increased too, which makes only the particles that have higher intensity level appear or makes a sudden variation of intensity level of the overlapped particles. In order to avoid the sudden variation of intensity level and to produce more exact centroids of particles, the particles' image is initially generated in a larger image, i.e., 2048 x 2048 pixel image.

3. Benchmark Test of 1-Frame 3D-PTV Technique for a Channel Flow

3.1 Principle of 3D measurements

3-D PIV is to measure the three-dimensional velocity vector components by tracking temporally the three-dimensional positions of particle tracers injected into flow fields. The principle of acquiring the three-dimensional positions of those particles in the flow is based on the stereo photogrammetry[10][11]. The three-dimensional velocity vectors of particles in flows are obtained by calculating the three-dimensional displacement of particle's positions during the time interval of image capture. The three-dimensional displacement of particle's position is obtained by finding the same pairs among numerous particles that had been captured with a different time interval. The three-dimensional position of a particle in space is obtained by finding the point that is intersected by the three collinears as shown in Fig. 4. Each collinear is calculated using each camera's parameters and the photographic coordinates of particles that have been viewed by each camera. Camera's parameters such as, center of projection, orientations, lens distortion, focal length, and deviation of principle point, are obtained by using a calibrator which has a three-dimensional positional information of several landmarks and their photographic coordinates[5]. Fig. 5(a), 5(b) and 5(c) show the virtual images of the calibrator viewed by the three cameras that have been installed as shown in Fig. 3. These images are generated by using the three-dimensional positional data of an actual calibrator and the cameras parameters, and by carrying out a calculation with Eqs. (1) and (2). The actual calibrator was

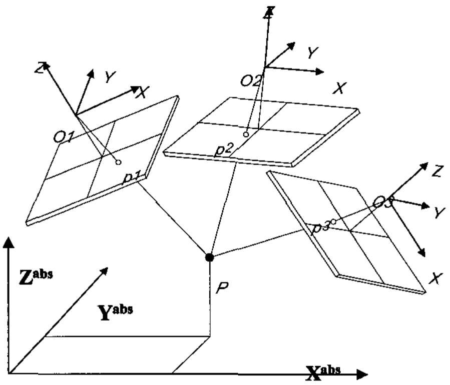
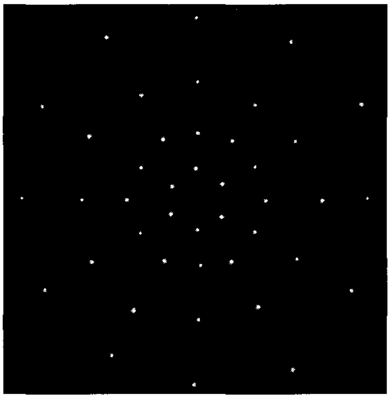
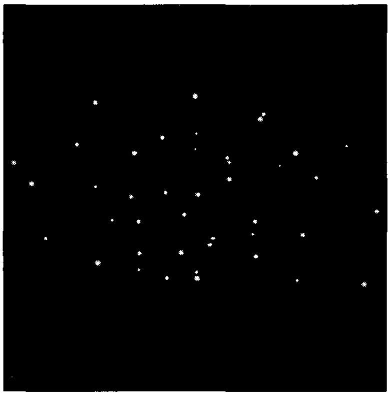


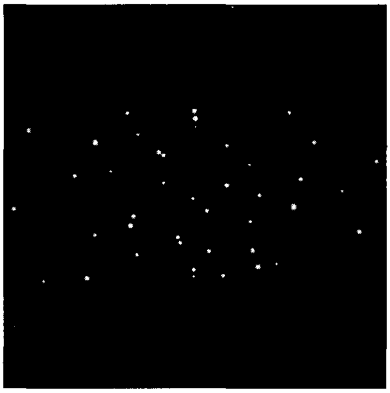
Fig. 4 Definition of 3D particle's position.



(a) viewed by camera 1



(b) viewed by camera 2



(c) viewed by camera 3

Fig. 5 Virtual images of the calibrator.

manufactured to carry out an actual velocity measurement of a channel flow as shown in Fig. 6. Using these virtual images, the parameters of the virtually installed three cameras are calculated. Tracking algorithm for the same particles which have different time interval is the 1-Frame 3D-PTV algorithm in which spatial match probability has been adopted.

3.2 Actual flow measurement on a channel flow with the 1-Frame 3D-PTV system

Experimental arrangement for the measurement of three-dimensional velocity distribution is shown in Fig. 6. The mean velocity, U, of the water channel is 0.5 m/sec. In order to measure the three-dimensional velocity of the flow, calibration of camera should be made. Three cameras were arranged perpendicular to the walls of the water channel in order to compare the measurement results with those of a virtual experiment of a benchmark test which will be discussed in the next section. The measurement system consists of three CCD cameras (768 x 494 pixels), an image grabber (512 x 512 pixels, 256 gray levels), an Ar-ion laser(5W), three video recorders, and a 32-bit host computer. In the experiment, the motions of the particles in a measuring volume have been observed by the cameras synchronized with AOM (Acousto-Optical Modulator)[12] that was used to enhance the dynamic range of velocity tracking by switching the Ar-ion laser source so that the illuminated time of the particles could be adjusted to any appropriate time. The images captured by the three cameras have been recorded onto three video tape recorders, VTR1 (Panasonic, AG-7350), VTR2 (Sony, SLV-RS1), and VTR3 (SLV-595HF), and have been sent to the image grabber (DT, DT3154) where the image signals of the three cameras are simultaneously converted from analogue to digital and have been stored on the memories of the host computer (256 gray levels). The above sequence of operations is carried out in 1/60s, and thus image data acquisition is repeated with 60Hz. After an image acquisition process had been finished, an image processing such as noise reduction and thresholding was carried out to get positional data of the particles′ centroids that are to be used in a calculation process of three-dimensional particles′ positions. This calculation process includes a process of camera calibration, a process of finding the same correspondent particle pairs. After finishing the calibration procedure as mentioned previously, tracer particles (Nylon 12, specific gravity 1.02) were seeded and the Ar-ion laser was illuminated toward the flow field through AOM. The images captured by the three cameras were transferred to the image grabber. Three-dimensional positions of the particles were calculated by using the centroids of particles appeared in the two sets of three cameras′ images and the obtained camera parameters[9]. Finally, three-dimensional velocity vectors were obtained by the same way explained in the previous section. Fig. 7 shows the actual image of particles viewed by camera 1. In this case, the number of particles appeared in the image were about 500. For this case, about 270 vectors were measured. Fig. 8 shows the measured 3D velocity vectors. This means that about 54% of particles were traceable with the measurement algorithm.

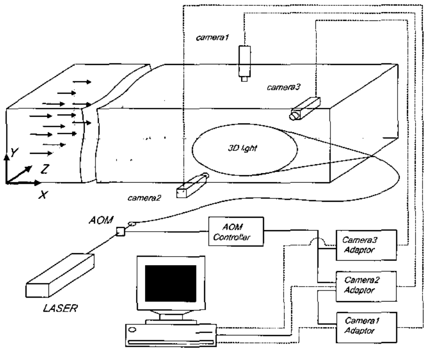


Fig. 6 Experimental setup for 3D-PTV measurement on a channel flow.

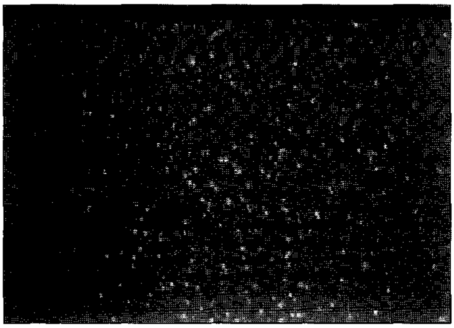


Fig. 7 Actual instantaneous image viewed by camera 1.

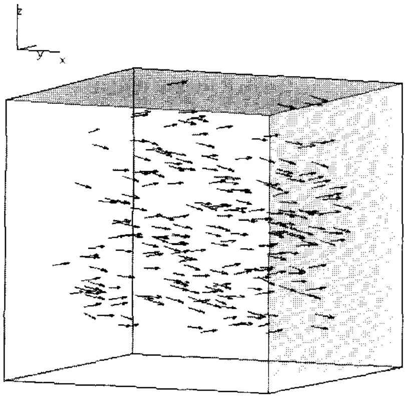


Fig. 8 Measured instantaneous 3D vectors for the channel flow.

3.3 Benchmark test of 1-Frame 3D-PTV

Fig. 9 shows virtual velocity vectors whose starting points were generated randomly in an interested measurement area and their terminals were decided by interpolating linearly using the LES data and the time interval. Fig. 10 shows the virtual image of particles generated in the generated virtually in the interested area 1.0H x 1.0H x 1.0H in Fig. 3 is 500. Fig. 11 shows the results of velocity vectors obtained by the 1-Frame 3D-PTV algorithm when the number of generated virtual particles is 500. About 65% of vectors were recovered. It is estimated

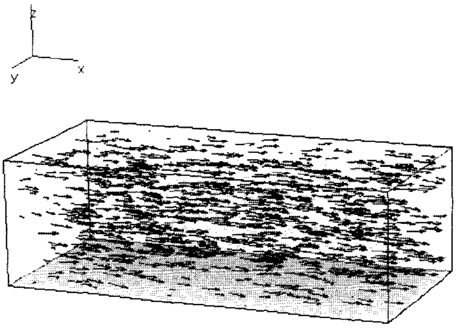


Fig. 9 3D virtual vectors selected in random.

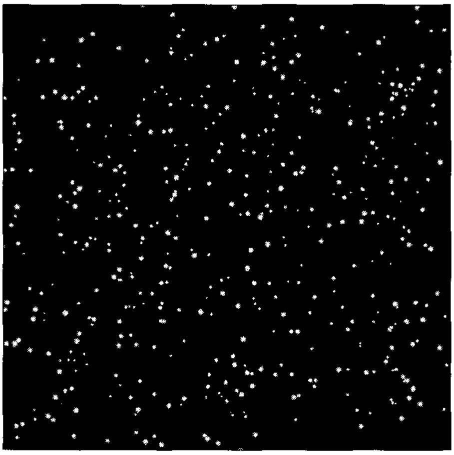


Fig. 10 Virtual image viewed by camera 1(N=500).

that the discrepancy, 11%, in the case of particle number 500 is mainly due to signal noises such as jittering and microwave influences. Fig. 12 shows a relationship between the recovered number of velocity vectors and the number of virtual particles initially generated. It can be seen that the recovered number of three-dimensional velocity vectors decreases with increase of virtual particle's number. It is construed that this phenomenon is due to the occlusion of many particles. And it can be said that an optimized number of particles can be estimated through this benchmark test using a set of virtual images.

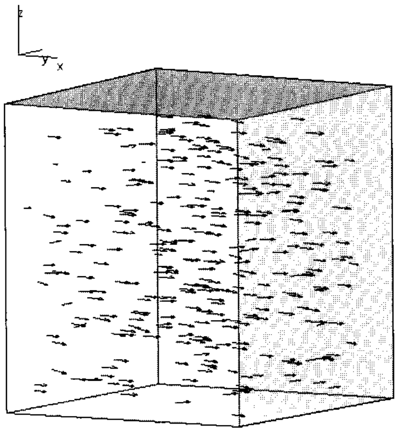


Fig. 11 3D vectors obtained by virtual image.

In this study, it was verified that the number of velocity vectors obtained by an actual experiment was fewer than that obtained by the benchmark test as made in the previous section. It is estimated that this reason is mainly due to some images noises and to the low pixel resolution of the camera's images.

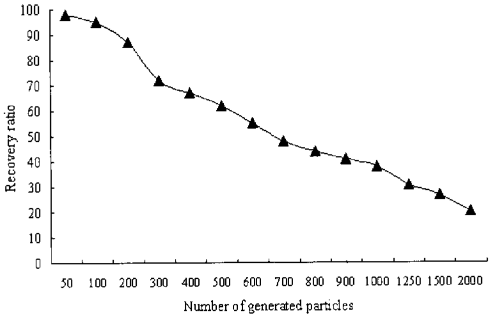


Fig. 12 Relations between the vector recovery ratio and the number of virtually generated particles.

4. Conclusions

Virtual images have been constructed to establish an evaluation tool for 3D-PTV techniques using the three-dimensional LES data sets. Through a benchmark test of 1-Frame 3D-PTV technique for a channel flow, it has been verified that there exists an optimal particle's density at which the number of velocity vectors becomes maximum value. It was verified through a benchmark test that some factors that affect the vector recovery ratio of 3D-PTV techniques was mainly due to some image noises and to the pixel resolution of images. The simulation code developed in this study can generate any kind of time-consecutive virtual images by using LES, DNS data sets or the results of a standard 3D-PTV experiment for various flow fields.

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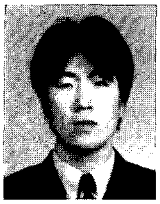

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