Development and Evaluation of an Improved Correlation Based PTV Method

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Abstract : An improved correlation based Particle Tracking Velocimetry (PTV) algorithm was proposed in the present paper. The path tracking of the tracer particles was achieved through a correlation operation of the small interrogation window around the studied tracer particles at two-time steps. The central positions of the tracer particles were determined by the correlation operation of the tracer particle image with a Gaussian particle mask in order to improve the accuracy to identify the central positions of particles up to sub-pixel level. The performance of the present improved correlation based Particle Tracking Velocimetry (PTV) algorithm was evaluated by using both synthetic VSJ standard PIV images and actual PIV images of a self-induced sloshing. Compared with other conventional PTV methods, the present improved correlation based PTV algorithm was found to be able to provide better solution and more robust for suppression the effect of background noise in the PIV images.

Keywords : particle tracking method, cross correlation, particle mask, VSJ standard PIV image.

1. Introduction

As a modern optical flow field measuring technique, Particle Image Velocimetry (PIV) can offer many advantages for the study of fluid flow over other conventional one-point measurement techniques like Laser Doppler Velocimetry (LDV) or Hot Wire Anemometer (HWA). PIV technique can measure the velocity of the whole two-dimensional or three-dimensional flow field instantaneously without disturbing to reveal the global structures of a complicated and/or unsteady flow field quantitatively. So it was widely used and rapidly developed in the past two decades.

At the current stage, the methods most widely used for PIV image processing can fall into two categories, i.e., the particle tracking methods and spatial correlation analysis methods (including auto-correlation method and cross-correlation method). Rather than tracking individual particles, the spatial correlation analysis methods are used to obtain the average displacement of the ensemble particles. The recorded PIV images were divided into many smaller sub-regions (which are called interrogation windows). Each interrogation window contains several particle images. Analysis of the displacement of images in each interrogation window by means of spatial correlation operation (either cross-correlation or auto-correlation method) leads to an estimated average displacement of particles included in the interrogation window (Adrian, 1991). The particle tracking methods are based on the tracking of individual particles with the time sequence. The trajectory paths of each individual particle were tracking through image processing. The methods based on the trajectory tracking of individual particles were also always named as Particle Tracking Velocimetry (PTV) algorithm (Kobayashi, et al., 1991).

In the present paper, an improved correlation based Particle Tracking Velocimetry (PTV) algorithm will be proposed. The path tracking of the tracer particles was achieved based on the correlation coefficient distribution of

a small interrogation window around the studied tracer particles at two-time steps. In order to improve the accuracy level of determination the central position of the particle, a Gaussian particle mask (Etoh and Takehara, 1998) was introduced in the present study to detect the centers of the tracer particles.

The performance of the present improved correlation based Particle Tracking Velocimetry (PTV) algorithm was evaluated by using both synthetic VSJ standard PIV images and actual PIV images of a self-induced sloshing. Compared with other conventional PTV methods, the present improved correlation based PTV algorithm was found to be able to provide better solution and more robust for suppression the effect of background noise in the PIV images.

2. The Present Improved PTV Algorithm

Generally, a PTV image processes method always includes two steps, which is (a) to identify the tracer particles from PIV images and (b) to track the trajectory paths of the tracer particles at successive time steps.

For the tracer particle identification from PIV images, conventional PTV methods always suffer from two problems. One is a number of particles can not be detected from the PIV images, and another is the accuracy level of the detection of particle centers. For the practical usage of PIV, PIV systems are always required to the following factors; simple algorithm, short time-step processing (e.g. consecutive two-time-step images), large number of instantaneous velocity acquisition and accurate measurement. For the particle tracking, PTV algorithms are always required to work simply and efficiently. In the present paper, corresponding to the requests for particle detection, a Gaussian particle mask was used to increase the number of the detected particles, and also to improve the accuracy of the detection of the particle center positions up to sub-pixel level. For particle tracking, a simplified algorithm was designed, in which the particle pairs were determined by calculating the correlation value of the small interrogation window around the studied particles at two-time steps. The cross correlation calculation of particle tracking is based on the particle positions.

2.1 Detection of Tracer Particle Position

Figure 1 shows an example of the PIV image pair at time steps T_0 and T_1. An enlarged figure of the window in T_0 image and its contours of the gray level are shown in Fig. 1(b) and Fig. 1(c) respectively. In order to detect the central positions of tracer particles with higher accuracy level, a Gaussian particle mask (Etoh and Takehara, 1998) is used in the present study, which is shown in Fig. 2(a). The particle mask is a 3×3 pixels mask with the image gray level distribution being Gaussian distribution. The whole PIV image is scanned and correlated with the mask pattern and the correlation distribution of the PIV image with the Gaussian particle mask can be obtained. The central position of the particle image is determined based on the correlation coefficient distribution instead of gray level of the PIV image. It was well known that the intensity of the scattering light from the tracer particle seeded in the flow field is usually in Gaussian distribution, so the image gray level distributions of the tracer particle images are in Gaussian distribution. While the gray level of the background noise is always random. Therefore the correlation operation of the Gaussian particle mask with PIV image suggested in the present paper can delete the effect of the various background noise compared with the other conventional methods based on the gray level of PIV image directly to determine the central position of the particle images.

Fig. 2(b) shows the distribution of the correlation coefficient values of the Gaussian particle mask with the PIV image window shown in Fig. 1(b). From the distribution of the correlation coefficient with a certain threshold, the particle domains can be identified, which is shown in Fig. 2(c). In each particle domain, the location with maximum correlation coefficient value is detected as the primary estimate of the center of the particle image. Then, four neighboring correlation coefficient values along with the peak correlation coefficient values were used to do sub-pixel interpolation to improve the accuracy of the estimated particle central position. The function used in the present paper to do sub-pixel interpolation is a two-dimensional Gaussion function, which is given in the following equation,

$$Pc = a \cdot \exp(-b \cdot (x-c)^2 \cdot \exp(-d \cdot (y-e)^2)$$
(1)

where a, b, c, d and e are five parameters determined by the peak correlation coefficient value with its four neighbors.
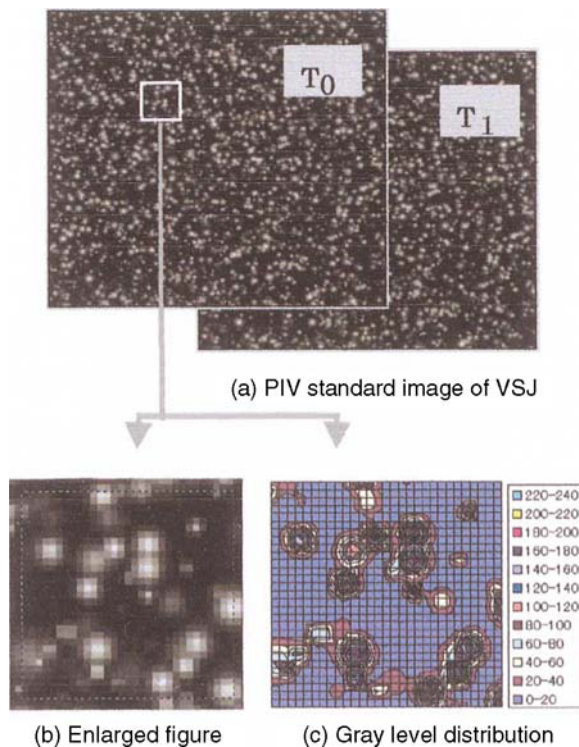
(a) PIV standard image of VSJ

(b) Enlarged figure (c) Gray level distribution

Fig. 1. An example of PIV image pair.

(a) Gaussian particle mask (b) Correlation coefficient distribution (c) Particle domains
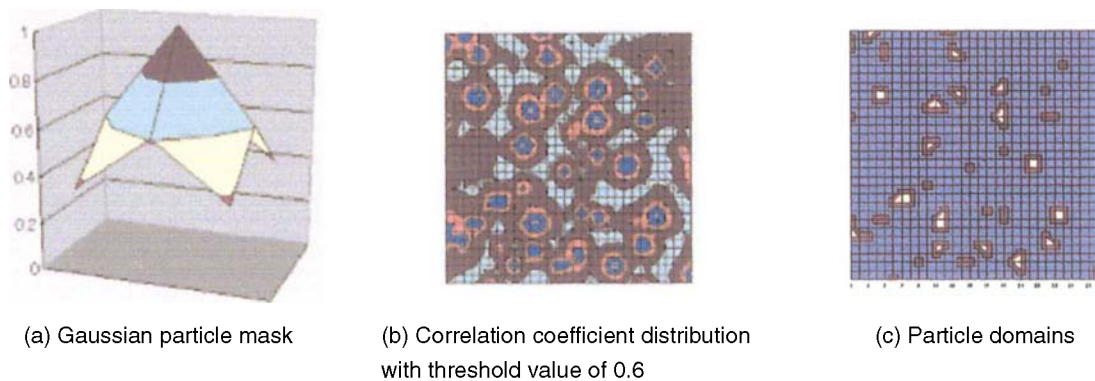with threshold value of 0.6

Fig. 2. Gaussian particle mask and correlation coefficient distribution.

2.2 Tracking of Particle

Figure 3 shows the schematic of the tracking process suggested in the present paper. Calculating the correlation value between the small interrogation windows W_0 and W_{1i} around the studied particles performs the particle tracking. The cross correlation calculation of particle tracking is based on the particle positions that are integer coordinate of the particle center Pc described in the above section. The particles pair is identified with the maximum cross correlation value of the candidate particles. Then the velocity vector is calculated from the center positions of identified particle pair with sub-pixel accuracy. Therefore, the particle tracking is pixel accuracy and the velocity measurement is sub-pixel accuracy. The procedures of the tracking process can be expressed as follows,

(1) To set an interrogation window W_0 around the studied particle T_{0i} in the PIV image of time T_0.

(2) To set another interrogation window W_{1i} centered at the particle T_{1i}, which is within the tracking range of A_{r1} in the PIV image of time T_1. Interrogation window W_0 and W_{1i} have the same size.

(3) To calculate the correlation coefficient R between the interrogation windows W_0 and W_{1i}.

(4) Finally, the particle in PIV image of time T_1 with maximum correlation coefficient value is considered to be the same particle as that in the interrogation W_0 of PIV image at time T_0.
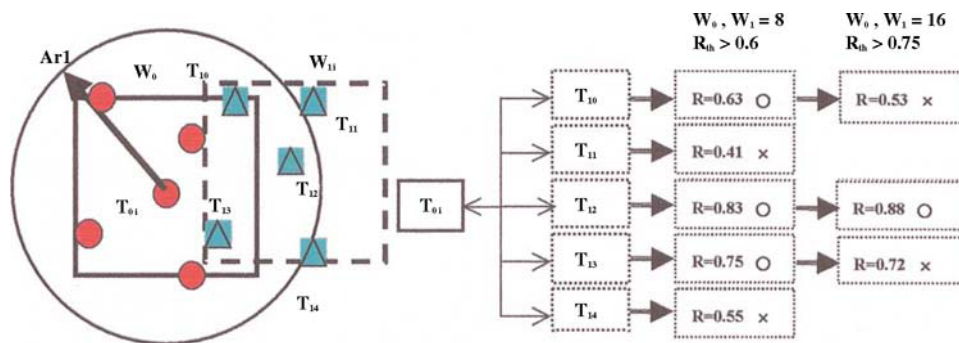
Fig. 3. The schematic of particle tracking algorithm suggested in the present paper.

In order to decrease the CPU computational time and improve the image processing speed, the size of the interrogation windows W_0 and W_{1i} was set to be very small (such as 8×8 pixel) at the first step. Since very small interrogation windows were used, unusually, similar cross correlation values are appeared in the calculation results which may be caused by the insufficient gray level information and/or image noise. In order to remove the erroneous particle tracking, a multiple-step procedure is used in the present study. In the case of erroneous particle tracking, the cross correlation value by the large size window (16×16 pixels) at second step decreases abruptly from the first step of the correlation value.

The multiple-step procedure operates as follows: at the first step, the correlation coefficient value distribution was calculated by using a small interrogation windows W_0 and W_{0i}, such as 8×8 pixel, then sort the correlation values with a threshold. If the correlation value is larger than the threshold value (such as, R_{th}=0.6), the particles are selected to be the candidate particles for the next step. For example, as the case shown in the Figure 3, there are three first-step candidate particles, T_{10}, T_{12} and T_{13} with the correlation values greater than threshold value 0.6, so they are selected to be the candidate particles for the second step. At the second step, the size of the interrogation windows is enlarged to 16×16 pixel, and conduct the correlation operation again for the candidate particles T_{10}, T_{12} and T_{13}. The particles with the correlation values larger than a new threshold (such as $R_{th} = 0.75$) are selected to be the candidate particles for the next new step. After two or three such iteration steps, the particle with maximum correlation value is considered to be the corresponding particle of the studied particle in the PIV image of time T_0.

3. Evaluation of the Performance of the Present PTV Algorithm

3.1 Evaluation of the Performance of the Present PTV Algorithm with VSJ Standard PIV Images

In order to evaluate the performance of the PTV algorithm suggested in the present study, the present PTV algorithm was used to do image processing of synthetic PIV images. The synthetic PIV images used in the present study are the VSJ standard PIV images, which are generated synthetically on the basis of Large Eddy Simulation (LES) results of a impinging jet flow (Okamoto et al., 1998). These VSJ standard PIV images were implemented by the Visualization Society of Japan (VSJ) and can be downloaded freely via INTERNET at site of http://www.vsj.or.jp/piv. The advantage of these VSJ standard PIV images is that the users can refer to the accurate particle displacement data, from which the image are generated, and compare the results of their particle tracking directly with those accurate results. The VSJ standard PIV images used in the present paper are 256×256 pixels 8-bit grayscale images. The main parameters of these PIV images were listed in Table 1. The particle number given in Table 1 is 4000. It means 4000 particles were seeded in the whole flow volume. However, it dose not correspond to the number of actually recognizable particles in the PIV images, because the laser-sheet is always much less than that of the constant flow volume in which the number of particle is distributed. The number of the particles can be actually tracking for the VSJ standard PIV images used in the present study is 1997.

Table 1. The main parameters of VSJ standard PIV images used in the present study.

Particle numbers in the flow field	4000 particles
Frames of the PIV images	2 frames
Thickness of the laser sheet	2 mm
Time interval between two image frames	5 ms
Averaged particle diameter	5 pixel
Standard deviation of the particle diameter	2 pixel

Table 2 shows the comparison of the accurate results and the image processing results obtained by using the PTV algorithm suggested in the present paper and another conventional PTV method such as Binary Correlation PTV method. The velocity vectors from the present algorithm and the binary correlation PTV method are shown in Fig. 4. It can be seen that the PIV image processing result obtained by using the present particle tracking method can agree with the accurate results. The velocity error distributions, defined as different from the velocity vectors obtained by image processing with the accurate results, are shown in Fig. 5. It can also be seen that the present algorithm has much higher accuracy level than the conventional PTV algorithm. For example, the present algorithm can improve the detection accuracy level of the central position of the particles and velocity vectors up to 0.05 pixel, while the accuracy level of the other conventional PTV method is always about 0.3 pixel.

Main reasons of the difference of both results are the detection method of particle position and the characteristic of processed images, gray level image and binary image. The conventional PTV method lost many image information at the binarization process.

Table 2. The comparison of the accurate result and the image processing result of the present algorithm and binary correlation PTV method.

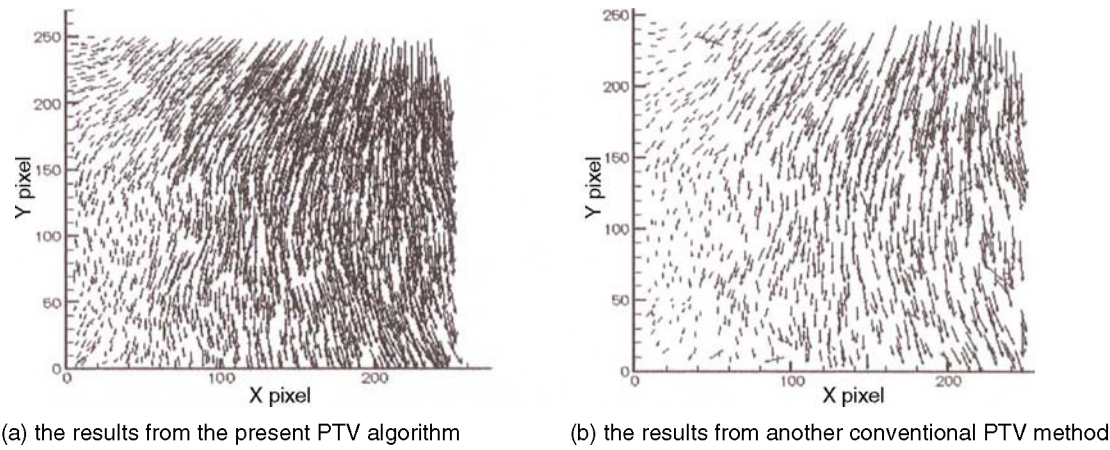|	Accurate solution	The results from the present PTV algorithm	The results from another conventional method
The number of the particle can be picked up (T_0)	1997	1933	1181
The number of the particle is exactly tracked	1592	1592	917
The number of the particle is tracked correctly	1592	1573	881
Path tracking error	0	9	36
Averaged velocity (pixel / frame)	3.59	3.57	3.54
The averaged error of the particle central position (pixel)	0	0.05	0.32
The deviation of the particle central position (pixel / frame)	0	0.1	0.29
The averaged error of the velocity vector (pixel / frame)	0	0.05	0.29
The deviation of the error velocity (pixel / frame)	0	0.1	0.22

(a) the results from the present PTV algorithm   (b) the results from another conventional PTV method

Fig. 4. The image processing results by using present PTV algorithm and another conventional PTV method.

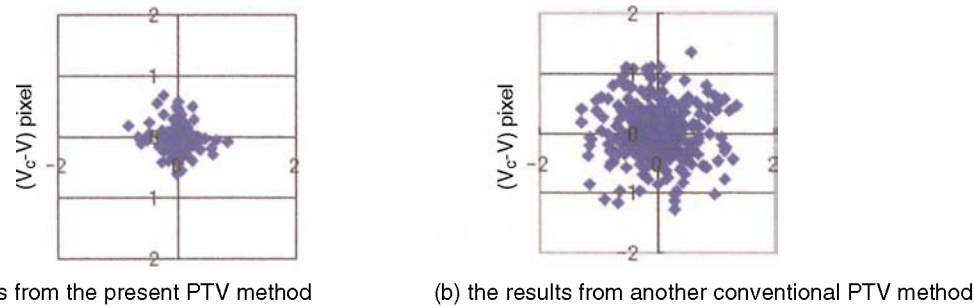(a) the results from the present PTV method   (b) the results from another conventional PTV method

Fig. 5. The comparison of the accuracy level of present algorithm with another conventional PTV method.

3.2 The Application of Present Algorithm to Conduct PIV Image Processing of a Self-induced Sloshing Flow

In the above section, the VSJ standard PIV images were used to evaluate the performance of the present algorithm. The VSJ standard PIV images used in the above context were generated without any background noise. However, for actual PIV images, there are always many noises, such as the non-uniformity of illumination and other optical effects. In order to test the effect of the background noise of the PIV images on the performance of the present PTV algorithm, the present PTV algorithm was used to do image processing of actual PIV images of a self-induced sloshing flow (Fig. 6).
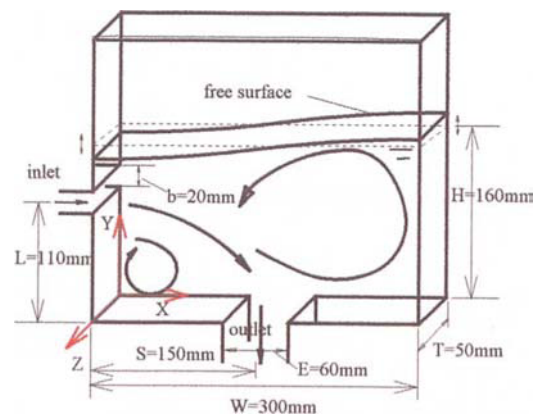

Fig. 6. The self-induced sloshing flow field in a rectangular tank.

The PIV system, used to obtain the PIV image of the self-induced sloshing flow, is composed of a double pulse Nd:YAG laser (output: 25 mJ/Pulse, wavelength: 532 nm, pulse duration: 6 ns, light sheet thickness: 2 mm), a high resolution cross correlation CCD camera (1008 × 1016 pixels, 8 bits) and a workstation (CPU 450 MH × 2, memory 1024 MB, hard disk 60 GB). The tracer particles are polystyrene particles with the average diameter being 35 mm and the gravity of 1.02. At the inlet of the rectangle tank, the average velocity is 0.333 m/s. The Reynolds number based on the width of the inlet and inlet velocity is about 6700. Figure 7(a) shows one example of the original PIV image captured by the PIV system. Figure 7(b) and Figure 7(c) give the velocity vectors by using present PTV method and the conventional binary correlation PTV method. From the comparison of the velocity vectors, it can be seen that the conventional binary correlation PTV method is almost invalid, while the present PTV method still can provide good result. It means that the performance of the binary correlation method is very sensitive to the background noise in the PIV images. However, the performance of the present PTV method is almost unaffected by the background noise in the PIV images. The reasons are supposed to be that the binary correlation PTV method is based on the binary particle image directly, so it is very sensitive to the non-uniformity of background gray level and image noise. The present PTV method had introduced a particle image mask to filter out the effect of the background noise, so the background noise almost has no effect on its performance.

(b) the results from the present PTV algorithm

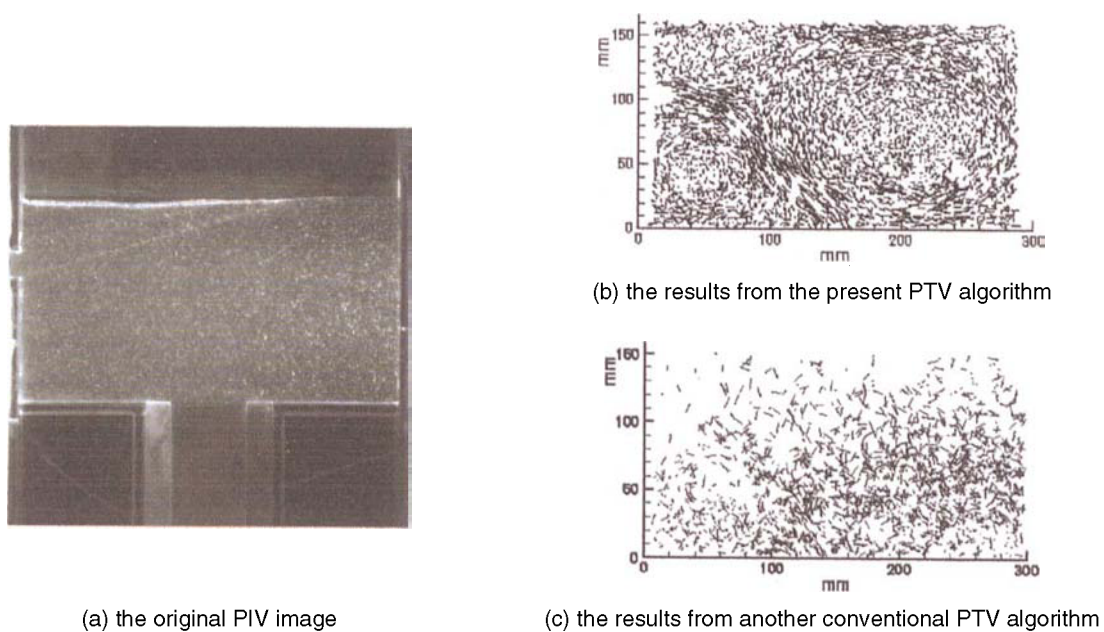(a) the original PIV image   (c) the results from another conventional PTV algorithm

Fig. 7. The original PIV image and PTV results from the present PTV measurement results and another conventional PTV method.

The measurement result of a Laser Doppler Velocimetry (LDV) system for the same self-induced flow is used to verify the result of the present PTV algorithm. For the LDV measurement, the distributions of the velocity and turbulence intensity of the self-induced sloshing flow field are measured at square grids of 10 mm pitch. The spatial resolution of the LDV result is about 0.68 mm × 65 mm, and the sampling rate is 1 kHz. The average diameter of the tracer particle for LDV measurement is about 1 mm. For the LDV measurement, the sampling period at every measurement point is 30 seconds (about 48 sloshing cycles), and about 30000 instantaneous data are obtained. The time averaged velocity and deviation of the velocity were calculated based on these instantaneous data.

On the other hand, for the PTV results, 2000 frames of PIV image pairs, which are taken in 133 seconds, were used to calculate the ensemble-averaged velocity and deviation of velocity. Since the frame rate of the PIV system is 15 Hz (9.4 image frames in a sloshing cycle), so totally about 213 cycles of self-induced sloshing were measured for the PTV results. Since the velocity vectors of PTV instantaneous results distributed randomly in the flow field, in order to get the ensemble values of the flow parameters, the instantaneous PTV results were interpolate to a 57 × 29 rectangular grid points. The ensemble-average velocity vectors are calculated by averaging all the instantaneous velocity vectors in the window of 16 × 16 pixels surrounding the gird points.

Figure 8 shows the ensemble-averaged PTV results at the rectangular mesh described in the above context.

The quantitative comparison of the present PTV results with LDV measurement results along the central line of inlet was given in Fig. 9. From the figure, it can be seen that the PTV results of the present algorithm agree well in general with the LDV measurement results both for ensemble-average velocity and velocity deviation. However, there are some local differences between the two results found in the velocity deviation profiles, which are supposed to be caused by the limited PTV frame number and the difference of spatial resolution of the two measurements.
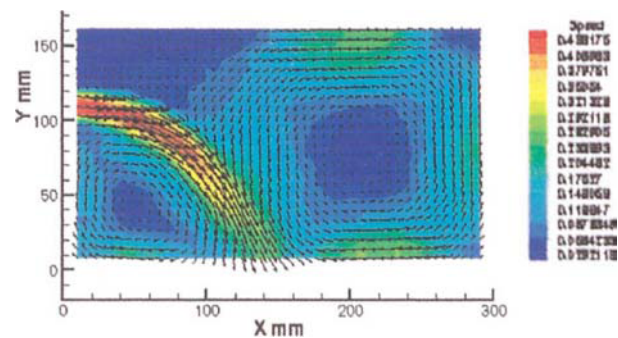

Fig. 8. The ensemble averaged flow field by using the present PTV method to do image processing.
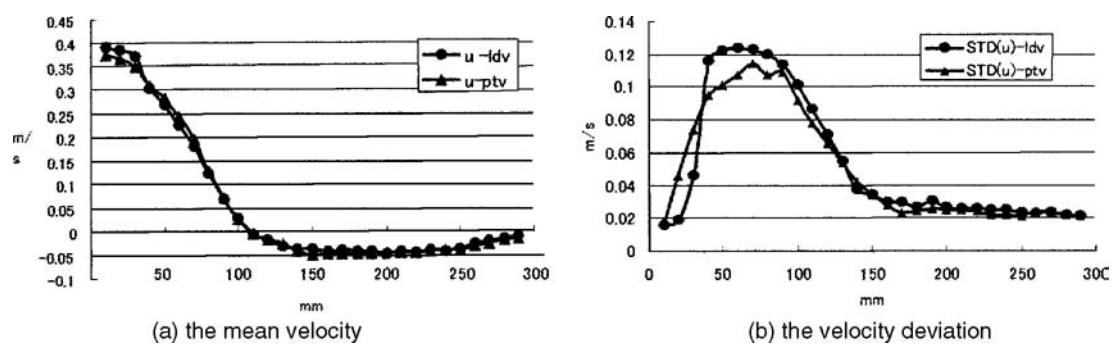

(a) the mean velocity   (b) the velocity deviation

Fig. 9. The comparison of the LDV measurement results with the results of present PTV method.

4. Conclusions

In this paper, an improved correlation based Particle Tracking Velocimetry was developed and its performance was evaluated by using both VSJ standard PIV images without background noise and the actual PIV images obtained in the PIV experiment of a self-induced sloshing flow field.

Based on the image processing results of the VSJ standard PIV images, it can be seen that both the averaged error and the deviation of the error between the accurate results and the image processing results obtained by using the present PTV method were found to be very small. It means that the present improved PTV algorithm can achieve the particle tracking with very high accuracy. The accurate level of the PTV result can be improved from about 0.3 pixel for the other conventional PTV methods to 0.05 pixel by using the present improved PTV algorithm.

By applying the present improved PTV algorithm to conduct image processing of actual PIV images of a self-induced sloshing flow, the PTV results from the present improved PTV algorithm were found to well agree with the LDV measurement results of the same flow field. It proved that the present algorithm is very robust to the effect of the background noise in the PIV images.

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