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Development and validation of stereoscopic micro-PTV using match probability [†]

Cheong-Hwan Yu[1], Jong-Hwan Yoon[2] and Hyoung-Bum Kim[1,3,*]

[1]*School of Mechanical and Aerospace Engineering Gyeongsang National University, Jinju, Gyeongnam, 660-701, Korea*
[2]*School of Automotive, Industrial and Mechanical Engineering Daegu University, Gyeongsan, Gyeongbuk, 712-714, Korea*
[3]*Research Center for Aircraft Parts Technology Gyeongsang National University, Jinju, Gyeongnam, 660-701, Korea*

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Abstract

A stereoscopic micro-PTV (particle tracking velocimetry) technique based on 2-frame PTV using match probability was developed. This method measures not only a two-dimensional velocity field but also the out-of-plane velocity component in micro fluid flow. A validation study of SMPTV by using a simulated flow model and a real micro jet flow was performed to verify the accuracy and feasibility of the method. The effects of different kinds of microscopes and the out-of-focus effect were also investigated. All test results were compared with the SMPIV method in order to evaluate the performance. The results showed that the SMPTV method using a CMO type microscope accurately measured the micro flow with the lowest bias error and higher spatial resolution than the SMPIV method.

Keywords: Stereoscopic micro-PTV; Stereoscopic micro-PIV; 2-frame PTV; Match probability; Stereoscopic microscope

1. Introduction

The development of CCD cameras with a laser light source and advanced digital image processing techniques have made the particle image velocimetry (PIV) system one of the core tools for flow measurement since the 1980s. Recently, research on micro fluidic devices has taken on greater importance due to their various fields of application. Since the possibility of micro flow measurement using the PIV method was introduced by Santiago et al. [1] in 1998, the micro-PIV technique has been widely used to study micro flow problems. Its success is in part due to difficulties in applying conventional flow measurement methods such as hot-wire and LDV to micro fluidic devices.

The key difference between the micro-PIV and conventional PIV method is the illumination method of the flow field. Micro-PIV measures the two-dimensional velocity field of the DOF (depth of focus) region under volume illumination, while the conventional PIV generally extracts the velocity information from a thin light sheet. Aside from this difference, the micro-PIV method has the same characteristics as the conventional PIV method. That is, it basically measures two-dimensional instantaneous velocity vectors and cannot resolve out-of-plane components of velocity vectors.

Numerous micro fluidic devices generate a three-dimensional flow. Measuring a three-dimensional flow field is very helpful to understand the physics of micro flow phenomena. Accordingly, various three-dimensional measurement methods for measuring micro flows have been introduced. Examples of these methods include the defocusing micro-PTV method [2], the 3D holographic micro-PTV method [3, 4], and the stereoscopic micro-PTV/PIV method [5-7]. These methods have respective strengths and drawbacks. A defocusing micro-PTV measures three-dimensional

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[*] Corresponding author. Tel.: +82 55 751 6076, Fax.: +82 55 762 0227
E-mail address: kimhb@gnu.ac.kr

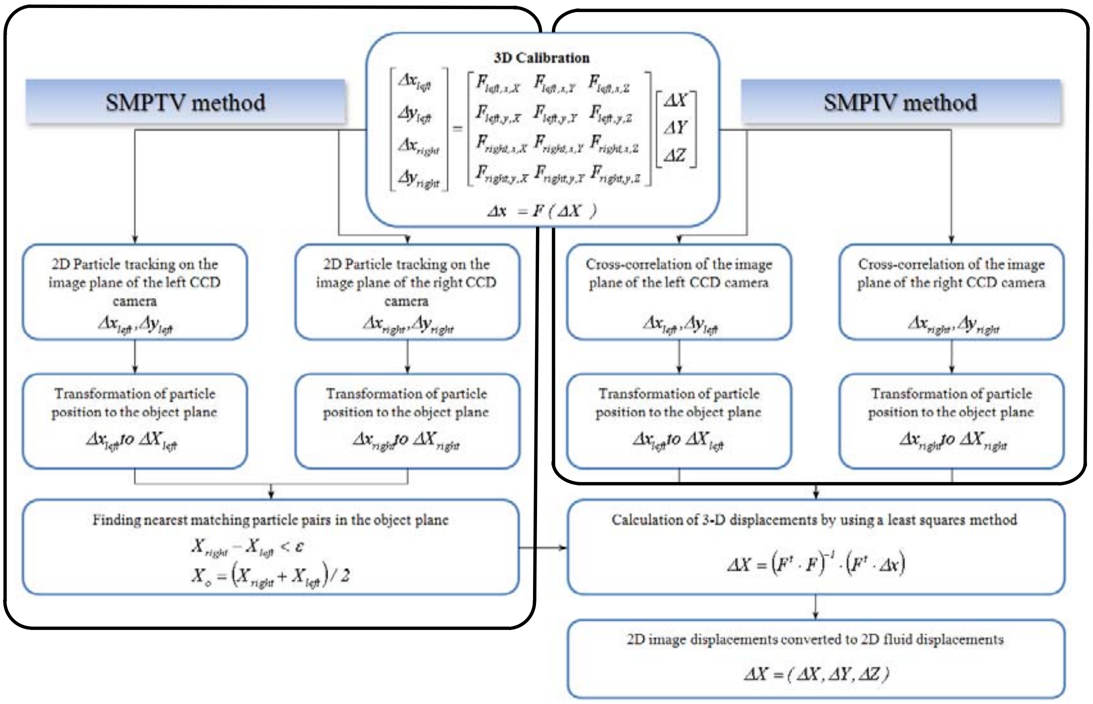


Fig. 1. Flowchart of data processing procedure of SMPTV/SMPIV method.

velocity in the volume of the measurement and shows good accuracy for the velocity along the depth direction. Difficulties related to image acquisition under low light power and low spatial resolution need to be addressed, however. Holographic micro-PTV offers excellent accuracy for the velocity along the depth direction. The requirement of high quality optics and low spatial resolution are problems that should be resolved. On the other hand, SMPTV/SMPIV can measure the out-of-plane velocity with adequate accuracy while involving easy system setup. These methods are micro versions of the conventional stereoscopic PIV technique.

The conventional stereoscopic PIV is widely used for measuring two-dimensional, three-component (2D3C) velocity of a fluid flow. The following is a brief description of this method. First, two cameras are needed to construct the stereoscopic configuration. After capturing the calibration image by using the calibration target plate, the mapping function between the image plane and object plane is obtained. From this mapping function, the third component of the velocity vectors is calculated from the other two measured velocity components.

One of the important variables that affects the performance of the SPIV and SPTV methods is the angle between two cameras. In traditional SPIV measurements, a camera angle between 20° and 30° has produced good results [8]. This range of camera angle can be easily achieved in a conventional SPIV system. However, the angle of the objective lens in the stereoscopic microscope system is much smaller than this optimal range. A recent study by Giardino et al. [7] showed the SPIV method under this small angle has less error than the predicted value by Lawson and Wu [8].

SMPIV gives the average velocity of the interrogation volume. As a result, if there is a velocity gradient in the interrogation window, the SMPIV method cannot resolve this gradient. In terms of spatial resolution, PTV can achieve higher spatial resolution than that of PIV by tracking each individual particle rather than employing cross-correlation between interrogation windows [9, 10].

In this study, we developed a new SMPTV method by applying a 2-frame PTV [10] to a stereoscopic microscope system. The key difference between the presently developed SMPTV and the previous SMPTV method [5] is the PTV algorithm used in the technique. In contrast to the previous SMPTV method, the SMPTV proposed in this study does not use the PIV information for particle tracking process. Although a hybrid PTV provides higher spatial resolution under a larger number density of seeding particles, the micro flow has a smaller number density of particles in general. In this case, the conventional PTV can give fast and accurate results [11, 12]. We performed a validation study of the SMPTV by using a simulated flow model and a real micro flow in order to verify the accuracy and feasibility of measurement. In addition, we quantitatively investigated the effect of out-of-focus and different types of stereoscopic microscopes in conjunction with the SMPTV method. All test results were compared with the SMPIV method to evaluate the performance.

2. Development of SMPTV using match probability

2.1 Stereoscopic micro PTV method

The SMPTV method utilizes a 2-frame PTV method based on the concept of match probability. Heuristics are used for calculating the matching probabilities of particle pairs between two consecutive images separated by a small time interval: the maximum velocity, a small velocity change, common motion, and consistent matching are assumed. To track the tracer particles while satisfying these heuristics, three matching parameters, maximum velocity (T_m), quasi-rigidity threshold (T_q), and neighborhood threshold (T_n), are used in the 2-frame PTV method. The algorithm for tracking discrete particles is based on the iterative estimation of match probability (P_{ij}) and no-match probability (P_i^*) as a measure of the matching degree. The iteration formula of $\tilde{P}_{ij}^{(n)} = A \cdot P_{ij}^{(n-1)} + B \cdot Q_{ij}^{(n-1)}$ is used to calculate the updated match probability $\tilde{P}_{ij}^{(n)}$ at each particle. Here, A(<1) and B(>1) are constants that affect the speed of convergence in the iteration. The superscript (n) denotes the iteration step number and Q_{ij} indicates the sum of all neighboring match probabilities for the displacement vector d_{ij}. The re-normalized match probability $P_{ij}^{(m)}$ is then used in the next iteration step (n+1). The no-match probability $P_i^{*(n)}$ is also updated to a normalized form. After successful particle tracking, correct matches have high probabilities and incorrect matches have very low probabilities. Finally, the velocity vector for the particle is calculated by using the tracked displacement vector d_{ij}, the time interval Δt.

Details of the main features and performance of the 2-frame PTV method are given in the references [10, 12]. The particle tracking algorithm using match probability is the main unique feature of the developed SMPTV method compared with the work by Bown et al.[5].

Fig. 1 shows a flowchart of the data processing routine of the developed SMPTV method. The data processing procedure resembles that of the SMPIV method except that, whereas the SMPIV method obtains an area-averaged displacement for each interrogation window, the SMPTV technique tracks individual particle centroids and uses a 3D calibration procedure to compensate for the image distortion and optical aberrations caused by stereoscopic imaging.

The calibration of the stereoscopic microscope image starts with obtaining calibration images with two stereoscopic cameras at three different out-of-plane locations parallel to the object plane. From these images, the mapping function between the 3D object field and 2D image plane for each camera is derived. In the SMPTV method presented here, these mapping functions are used during reconstruction to determine the particle displacements without any geometric information on the optical system. The relationship between the 3D object volume and 2D image planes for two cameras can be written as $\underline{\mathrm{X}} = \mathrm{F}(\underline{\mathrm{x}})$, where $\underline{\mathrm{X}}$ is the projected image position of the particle, $\underline{\mathrm{x}}$ is the real particle position in the object volume, and the mapping function $\mathrm{F}(\underline{\mathrm{x}})$ is approximated by a third order polynomial expression. The particle displacement in the projected image $\Delta\mathrm{X}$ can be approximated as $\nabla\mathrm{F(x)}\cdot\Delta\mathrm{x}$. The 2D displacement data of the left and right image planes are calculated by using the 2-frame PTV scheme, and particle positions are transformed into the object plane in physical coordinates. Matched particle pairs having the shortest particle distance are then found. The augmented matrix for each individual particle pair is subsequently formed by using the predetermined 3D calibration data, after which the final out-of-plane displacements of the particle are calculated.

In SMPIV, on the other hand, the 2D PIV data transformed into the object plane from the left and right cameras do not correspond with each other. Because the final PIV results do not contain any information on the real particle centroids, the evenly distributed left and right 2D PIV data must be interpolated into new rectangular grid points of the object plane, where the final SMPIV data are extracted by solving the augmented matrix. This supplementary interpolation procedure, which is not required in the SMPTV method, may introduce additional errors.

2.2 Stereoscopic microscope system

The SMPTV method uses a stereoscopic microscope system for the experimental apparatus and two types of stereoscopic microscopes are employed, a Greenough type and a CMO (common main objective) type, both of which are schematically illustrated in Fig. 2. The Greenough type consists of two identical and symmetrical optical systems, each containing a separate objective lens arranged in accurate alignment, whereas the CMO type has a common main objective lens, through which both the left and right routes view the object. Each route operates as an independent optical train parallel to the other and there is collimated light between the individual routes and the objective. This arrangement guarantees that convergence of the left and right optical axes coincides with the focal point in the specimen plane.

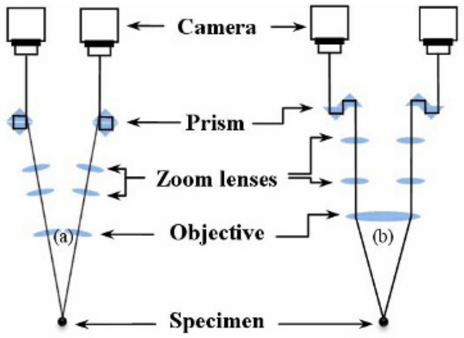


Fig. 2. Schematics of stereoscope configurations with CMO and Greenough type microscope systems: (a) Angular displacement with Greenough type and (b) Translation with CMO type.

These different microscopes have respectively unique characteristics. The CMO type offers the advantage of sharpness throughout the entire field of view (FOV) and can be easily fitted with a polarizing attachment. However, non-paraxial optics is a disadvantage of this type. This problem is caused by the beam paths not passing through the center of the CMO lens, which makes the image axially asymmetrical.

The Greenough type has a very limited area where the three-dimensional specimen appears sharply in both beam paths due to the tilted beam path. The correction for optical aberrations in this type is easier than for the CMO type, because the objective lenses are smaller, axially symmetrical, and do not rely heavily on light rays passing through the objective periphery. Due to its tilted beam path, the Greenough type has larger DOF than the CMO type microscope [13]. Finally, the CMO type microscope gives translational configuration of stereoscope imaging and the Greenough type provides an angular displacement type of stereoscope configuration.

In this study, we investigated the effects of these different stereoscopic configurations on the velocity results of the SMPTV and SMPIV methods by using a simulated flow model.

Two stereomicroscopes were used to compare the CMO type (M205C®, Leica Co.) with the Greenough type (SZ-60®, Olympus Co.). The DOF (∂z) of the digital imaging systems is defined by Eq. (1) [14]. λ is the wavelength of the illuminating light, η represents the refractive index of the medium between the objective lens and the specimen, d_r is the resolution of the recording system, M is the total magnification of the objective, and NA is the numerical aperture.

$$\partial z = \left(\frac{\eta \cdot \lambda}{NA^2}\right) + \left(\frac{\eta \cdot d_r}{M \cdot NA}\right) \tag{1}$$

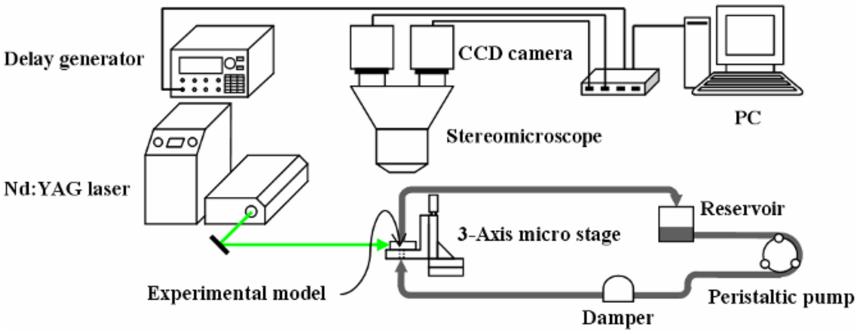


Fig. 3. Schematic diagram of experimental setup.

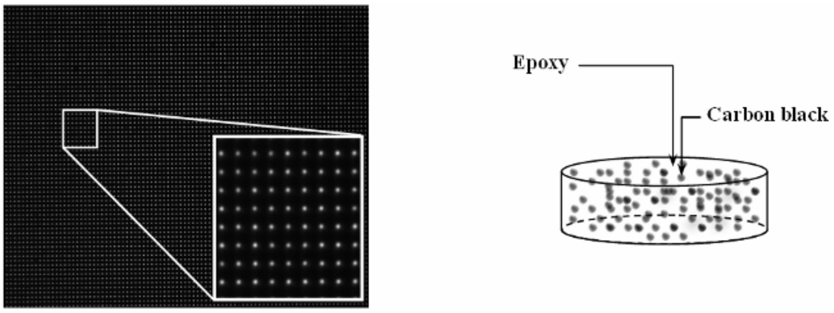


Fig. 4. Simulated flow model for investigating out-of-focus effect: (a) Flow model without out-of-focus effect and (b) Flow model with out-of-focus effect.

The CMO type was equipped with an objective lens (PlanApo 2.0×) with NA = 0.35. The zoom ratio on this microscope allows magnification from 1 to 20.5. This CMO stereomicroscope has a maximum DOF at the lowest zoom ratio, i.e., 18.6μm, and a minimum DOF at the highest zoom ratio, i.e., 5μm. The Greenough type stereomicroscope has a small zoom ratio from 1 to 6.3 and the objective lens has a low numerical aperture (NA=0.13). This objective lens has a DOF of about 38.7μm ~ 60μm, which is larger than that of the CMO type and is a characteristic of a Greenough type microscope [13].

The maximum magnification of M205C® is about 15× and this is lower than that of conventional microscope using higher objective lens (>20×). Thus, the spatial resolution of SMPTV also can be decreased. To increase the spatial resolution, the ensemble averaging or using relay optics between the microscope and camera will improve the spatial resolution [7].

Fig. 3 presents schematic diagram of the stereoscopic micro imaging system used in this study. The flow field was illuminated by a double-pulse Nd: YAG laser (Solo III®, NewWave Co.) with a wavelength of 532nm. Two CCD cameras were mounted directly behind two tubes of the microscope. Both cameras had a resolution of 1600×1200 pixels with 8-bit grayscale output.

The calibration plate for the stereoscopic system was made of a thin film. It consisted of an array of white points on a black background illuminated by white LED light. This target was made by the same process used in the design of masks for MEMS fabrication. The printing accuracy of this target is less than 0.5μm. The calibration images were acquired by moving the target along the z-axis. The entire depth-of-focus (DOF) volume could be covered in this manner. The flow model was located on a 3-axis micro stage and the working fluid was driven by a peristaltic pump, and a flow damper was used to remove the pulsating effect of the peristaltic pump.

The SMPTV and SMPIV methods are affected by the diffused reflection of particles located in the out-of-focus region, because these methods are difficult to illuminate only a thin slice of the flow field with a laser sheet like conventional PIV. Therefore, the particles of the outside depth of focus appeared as a blurred image. On the other side, the particles in the region of depth of focus appear sharply. It affects the accuracy of the measurement by SMPTV/SMPIV methods. The effect of the out-of-focus particle image on the micro PIV measurement was investigated by Olsen and Adrian [15]. They proposed the depth of correlation by considering this out-of-focus effect in the 2D micro PIV method. In this paper, we investigated the out-of-focus effect of the SMPTV and SMPIV methods in conjunction with a stereoscopic microscope by using a simulated flow model. The flow model, which had no out-of-focus particle images, was a thin film having 5μm spots with 15μm grid spacing similar to the calibration target. The simulated flow model with out-of-focus effect was made as shown in Fig. 4. Epoxy resin (η_{epoxy}=1.5) mixed with carbon black particles was poured into a culture dish. The flow model simulating the out-of-focus effect was used after the epoxy resin solidified. The simulated flow models were precisely moved from 3μm to 10μm with 1μm intervals along the z-axis and from 0 to 10μm with 5μm intervals along the x-axis. This procedure was repeated 50 times.

2.3 Micro jet flow measurement

The micro jet flow measurement using the SMPIV and SMPTV methods, respectively, was performed to validate this technique for a real fluid flow problem.

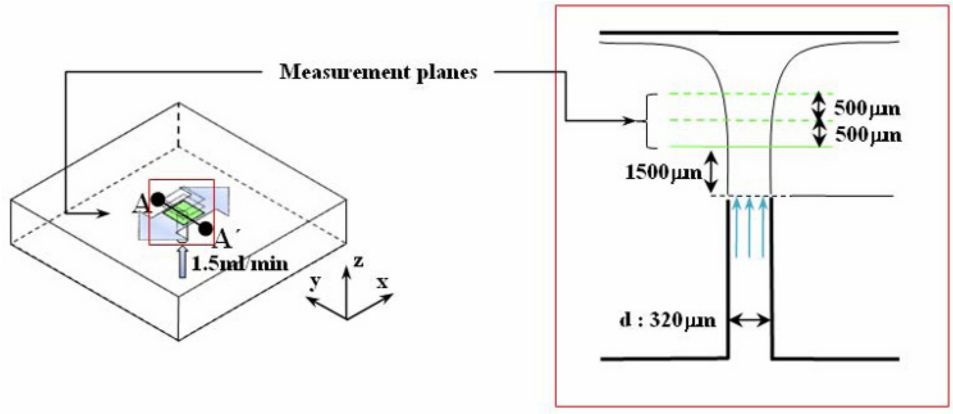
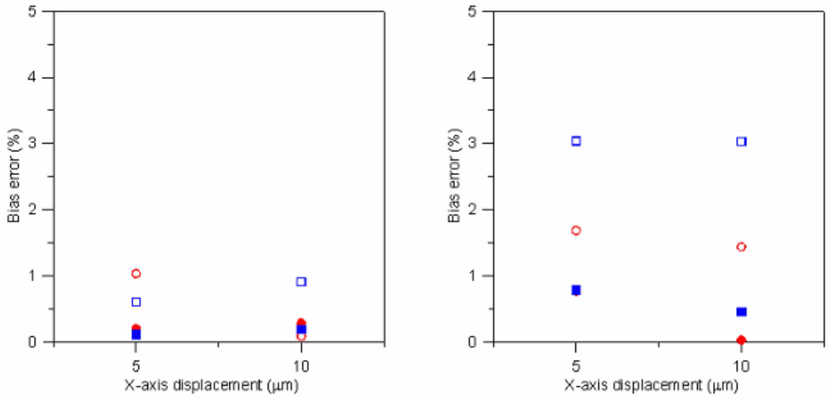


Fig. 5. Schematic diagram of micro jet flow apparatus.



(a) (b)

Fig. 6. Comparison of bias error of x-axis displacement measurement: (a) Without out-of-focus effect and (b) With out-of-focus effect (● SMPTV with CMO type, ○ SMPTV with Greenough type, ■ SMPIV with CMO type and □ SMPIV with Greenough type).

Fig. 5 shows the geometry of the test section. The working fluid was distilled water, which was injected into a channel from a nozzle (d=320μm) at the center of the test model. The flow rate was 1.5 ml/min. Polystyrene microspheres with 1μm diameter were used as seeding particles. The test model was located on the 3-axis micro stage and the velocity measurement was carried out in a total of 3 planes along the z-axis. The distance between the consecutive planes was 500μm.

In general, the calibration target is located on the measurement plane in the working fluid, and the conventional SPIV does not need to compensate for the multimedia geometry in this configuration. In the SMPIV and SMPTV methods, because stereoscopic calibration was performed under different conditions, it is necessary to compensate for this multi media geometry effect, which results from variation in the refraction index (air (η_{air}=1), glass (η_{glass}=1.5) and water (η_{water}=1.33)) [16].

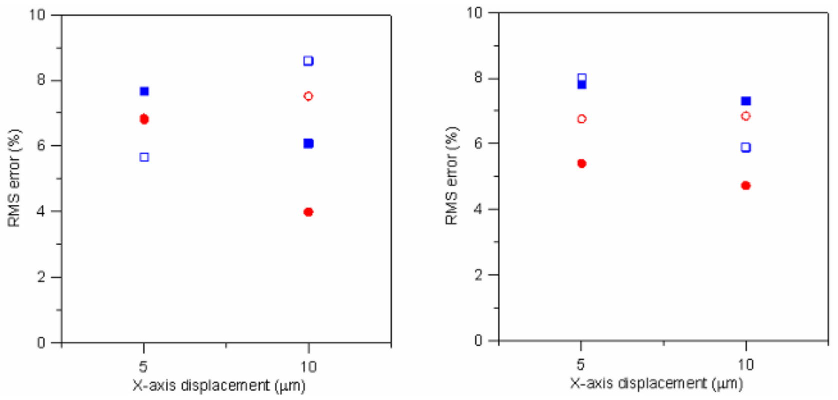
3. Results

3.1 The simulated flow model test

In order to compare the experimental data with the true displacement ($\delta_{true}=\Delta x_{true}, \Delta z_{true}$), an analysis was carried out on the measured displacement data ($\delta=\Delta x, \Delta z$). The bias error is defined as follows:

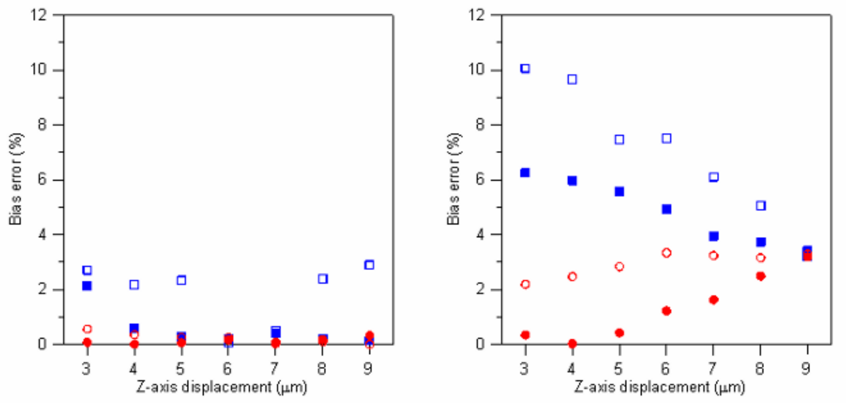
$$\varepsilon_{bias} = 100 \times \frac{|\delta_{true} - \delta|}{\delta_{true}} \quad (2)$$

and the rms error is given as



(a) (b)

Fig. 7. Comparison of rms error of x-axis displacement measurement: (a) Without out-of-focus effect and (b) With out-of-focus effect (● SMPTV with CMO type, ○ SMPTV with Greenough type, ■ SMPIV with CMO type and □ SMPIV with Greenough type).



(a) (b)

Fig. 8. Comparison of bias error of z-axis displacement measurement: (a) Without out-of-focus effect and (b) With out-of-focus effect (● SMPTV with CMO type, ○ SMPTV with Greenough type, ■ SMPIV with CMO type and □ SMPIV with Greenough type).

$$\varepsilon_{rms} = \sqrt{\frac{\sum_{k=1}^{n}\left(\delta_{true,k}-\delta_{k}\right)^{2}}{n}} \qquad (3)$$

Figs. 6(a) and (b) show the bias error of the x-axis displacement measurement by using the SMPTV and SMPIV methods. The bias error of the measured displacement from SMPTV and SMPIV was less than 1% for both the Greenough and CMO type when there was no out-of-focus effect. When there was an out-of-focus effect, the bias error of the SMPIV results increased slightly. The results of SMPIV using the Greenough type microscope showed the largest bias error, 3%. This was due to the larger DOF of the Greenough type microscope. The amount of x-axis displacement did not affect the accuracy of the measurement. By using SMPTV, the smallest error was obtained regardless of the presence of the out-of-focus effect. SMPTV with the CMO type microscope showed lower bias error than that with the Greenough type microscope. From the x-axis displacement test, we confirmed that both the SMPTV and SMPIV can measure the displacement precisely and the effect of the different microscope was small for this in-plane measurement.

Figs. 7(a) and (b) show the rms error for the same conditions as Fig. 6. Rms error of 4 to 8% was observed. From these results, it was determined that the random error was invariant regardless of the type of microscope, the out-of-focus effect, and the SMPTV/SMPIV method.

These x-axis displacement results showed that both the SMPTV and SMPIV method can measure the in-plane motion with high accuracy. Furthermore, although the Greenough type had a slightly larger bias error than that of the CMO type, the difference was small. In general, SMPTV always yielded the lowest bias error and similar rms error compared with the SMPIV method with the same kind of stereoscopic microscope.

Figs. 8(a) and (b) present a comparison of the bias error from the z-axis displacement measurement. From the results, it was found that, when there was no out-of-focus effect, SMPIV using the Greenough microscope yielded the largest bias error. In the case of SMPTV, the smallest bias error, i.e., less than 1%, regardless of the type of microscopic system was obtained. This level of bias error was the same as that for the x-axis displacement measurement. When there was an out-of-focus effect, the bias error of all cases increased. SMPTV showed the lower bias error compared with the SMPIV method and this difference became more pronounced as the z-axis displacement decreased. As the z-axis displacement increased, the difference of the bias error between the SMPIV and SMPTV method decreased, and it saturated at around 3% of bias error.

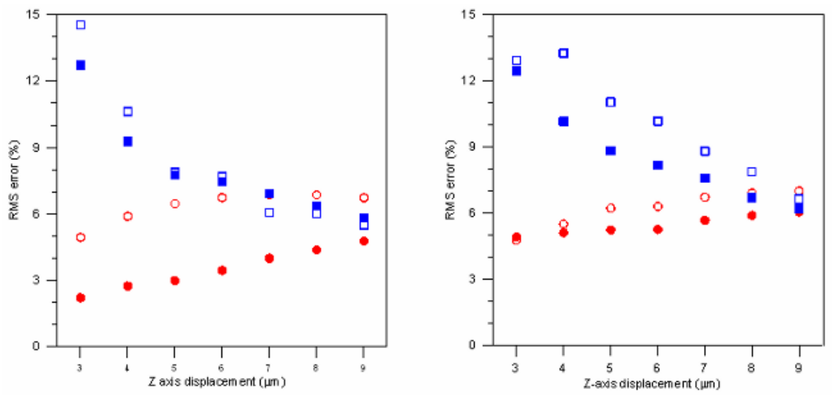
SMPTV requires accurate measurement of the centroids location. As the z-axis displacement increased, the particle image became blurred and the error of peak detection for the centroids increased. Therefore, the bias error also increased.

For different microscopes, the Greenough type always had larger bias error for both the SMPTV and SMPIV method.

Figs. 9(a) and (b) are a comparison of the rms error between the SMPTV and SMPIV methods with different microscopes and with and without the out-of-focus effect. The results correspond well with the bias error results. The SMPTV method showed lower rms error and this difference decreased as the z-axis displacement increased. The CMO type microscope had lower rms error than that of the Greenough type microscope for both the SMPTV and SMPIV method. The rms error of SMPTV was below 7% in general, which is the same level as the x-axis displacement and is much smaller than the rms error reported by Lawson and Wu [8].

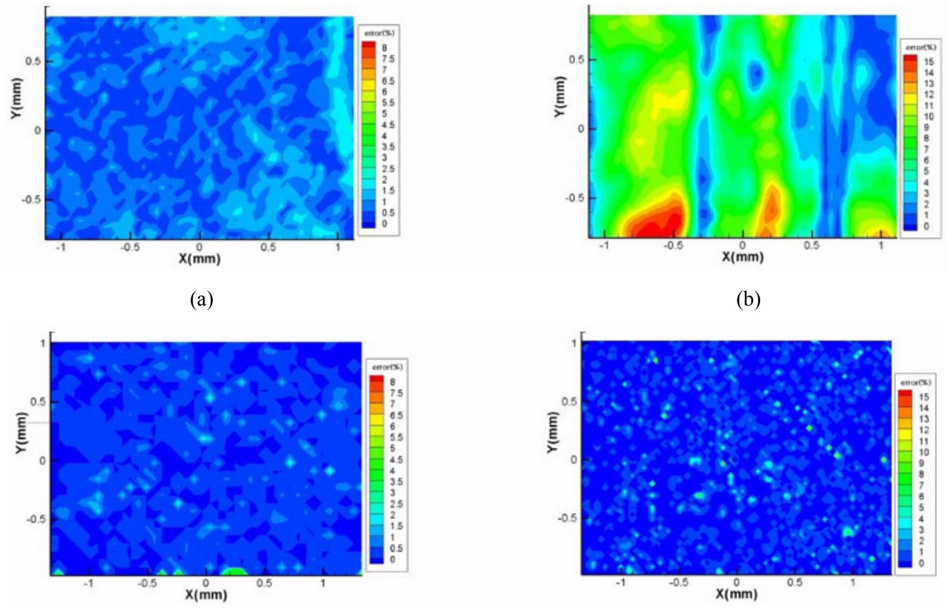
The rms error was not affected by the out-of-focus effect, similar to the x-axis displacement. This means the out-of-focus affects only the bias error. The distribution of the bias error between SMPIV and SMPTV methods was compared. The results of SMPTV were interpolated data, because the original results from SMPTV were randomly distributed around the measurement field.

Fig. 10 shows the contour results of the bias error comparison from 5μm displacement movement along the z-axis. The bias error from SMPIV showed a clear banding distribution, and this banding became clear when there was an out-of-focus effect. Giardino et al [7] also reported this phenomenon and said that it was



(a) (b)

Fig. 9. Comparison of rms error of z-axis displacement measurement: (a) Without out-of-focus effect and (b) With out-of-focus effect (● SMPTV with CMO type, ○ SMPTV with Greenough type, ■ SMPIV with CMO type and □ SMPIV with Greenough type).



(a) (b)

(c) (d)

Fig. 10. Comparison of contour graph of bias error from z-axis displacement measurement: (a) Bias error of SMPIV without out-of-focus, (b) Bias error of SMPIV with out-of-focus, (c) Bias error of SMPTV without out-of-focus and (d) Bias error of SMPTV with out-of-focus.

due to distortions in the calibration target that resulted in slightly non-uniform non-coplanar grid spacing. In the case of the SMPTV results shown in Fig. 10, there was no banding effect and the bias error was randomly distributed. The same stereoscopic calibration process was used for both the SMPIV and SMPTV methods. From these results, it is concluded that the SMPTV can avoid this kind of local distribution of bias error appearing with the SMPIV technique.

3.2 Micro jet flow measurement

The simulated flow model study cannot reveal the entire performance of SMPTV due to a lack of shear, noise, etc. Therefore, real flow measurement is needed for validation. SMPTV was used to measure the micro jet flow and the results were compared with those for the SMPIV method. Fig. 11 shows the instantaneous velocity vectors from the SMPIV and SMPTV methods. The qualitative results showed high momentum in the center region of the jet passing through the nozzle. This momentum was transferred to the side region proceeding downstream. These results show that the developed SMPTV method can qualitatively measure the micro jet flow well with higher yield of velocity vectors. The spatial resolution of SMPIV was 47.4μm using 64×64 (pixel) interrogation windows. In the case of SMPTV, we defined the spatial resolution as the mean distance between the nearest neighborhood velocity vectors, arriving at 26.2μm. Thus, SMPTV has higher spatial resolution than the SMPIV method.

We quantitatively verified the SMPTV method, and Fig. 12 shows the magnitude of the w-velocity component along the $\overline{AA'}$ line of Fig. 5. From this, we calculated the volume flow rate by assuming an axisymmetric condition of the circular jet and integrating the velocity (Eq. (4)). This was repeated for the SMPIV results, and both results were compared with the flow rate from the peristaltic pump calibrated by a balance. The difference (ε_r) between the calculated volume flow rate (Q_{exp}) and the flow rate (Q_{pump}) from the peristaltic pump was about 5.5% for SMPIV and 2.6% for SMPTV. This means that the SMPTV method also can quantitatively measure the micro jet flow with higher accuracy than the SMPIV method.

$$Q_{\exp} = \int \vec{w} A$$
$$\varepsilon_r = \frac{Q_{pump} - Q_{\exp}}{Q_{pump}} \times 100 \tag{4}$$

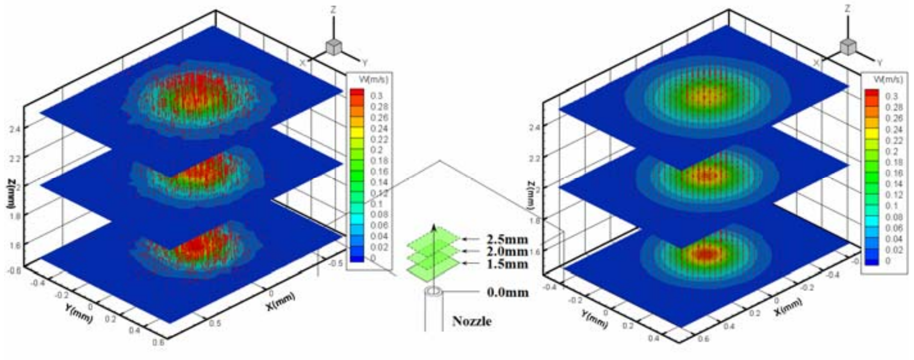


Fig. 11. Instantaneous velocity vector results from micro jet flow measurement using SMPTV/SMPIV method: (a) Instantaneous velocity vectors of SMPTV and (b) Instantaneous velocity vectors of SMPIV.

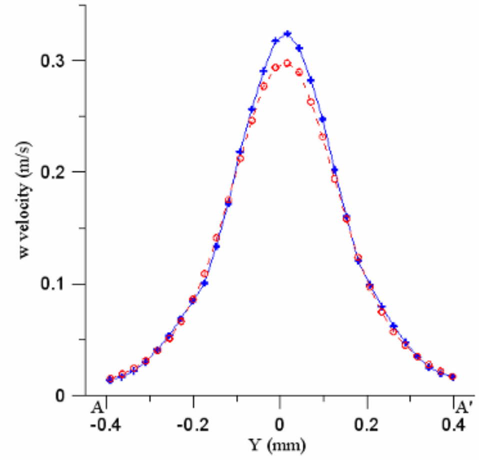


Fig. 12. Comparison out-of-plane velocity profile at $\overline{AA'}$ line shown at Fig. 5 (○ SMPIV + SMPTV).

4. Conclusions

In this study, we developed a new micro three-dimensional flow measurement technique by combining a stereoscopic microscope and the 2-frame PTV method using match probability. From the present study, we found that the type of microscope slightly affects the results. Specifically, the CMO type provides lower bias and rms error than the Greenough type microscope. This is due to the Greenough type microscope having a smaller overlap region between the left and right viewing area and larger DOF relative to the CMO type.

The out-of-focus effect only increases the bias error and does not affect the rms error regardless of the microscope type and SMPTV/SMPIV method.

SMPTV always yields smaller bias error than that of the SMPIV, and the difference is quite pronounced when the z-axis displacement is small. That is, the SMPTV method measures the low speed out-of plane motion with higher accuracy than the SMPIV method. In the case of rms error, SMPTV provides the same level of rms error for both the x-axis and z-axis displacement measurement.

The results from real flow measurements confirmed that SMPTV can measure the micro flow with higher spatial resolution and accuracy relative to the SMPIV method.

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Hyoung-Bum Kim received his M.Sc. and Ph.D. in Mechanical Engineering from POSTECH in 2000. He worked in the Department of Mechanical Engineering of the University of Colorado, Boulder till 2004 as a post-doctoral researcher and then in 2004 joined the School of Mechanical and Aerospace Engineering at Gyeongsang National University as an assistant professor. His research interests are in flow measurement and control using optical and ultrasound method, turbulent shear flow, flow instability and bio-fluid flow.

Cheong-Hwan Yu received his B.Sc. degree in Mechanical Engineering in 2007 from Gyeongsang National University and is now a master's degree student at the Graduate School of Mechanical and Aerospace Engineering, Gyeongsang National University. His research interest is micro flow measurement and POD analysis.

Jong-Hwan Yoon received his M.Sc. and Ph.D. in Mechanical Engineering from POSTECH in 2003. He worked in Doosan Heavy Industry till 2004 and then joined the School of Automotive, Industrial and Mechanical Engineering at Daegu University. He is interested in 3-component flow measurement techniques using optical methods and flow induced noises and vibrations.