Proceedings of 2001 Korea-Japan Joint Seminar
on Particle Image Velocimetry
Seoul National Univ., Dec. 3 - 4

3D Particle Image Detection by Using Color Encoded Illumination System

M. Kawahashi, H. Hirahara

Department of Mechanical Engineering
Saitama University
Saitama 338-8570, Japan

Abstract

A simple new technique of particle depth position measurement, which can be applied for three-dimensional velocity measurement of fluid flows, is proposed. Two color illumination system that intensity is encoded as a function of z-coordinate is introduced. A calibration procedure is described and a profile of small sphere is detected by using the present method as preliminary test. Then, this method is applied to three-dimensional velocity field measurement of simple flow fields seeded with tracer particles. The motion of the particles is recorded by color 3CCD camera. The particle position in the image plane is read directly from the recorded image and the depth of each particle is measured by calculation of the intensity ratio of encoded two color illumination. Therefore three-dimensional velocity components are reconstructed. Although the result includes to some extent error, the feasibility of the present technique for three-dimensional velocity measurement was confirmed.

1. Introduction

Quantitative visualization of velocity, density or temperature field has contributed to understanding physical phenomena of complicated fluid flows. Especially, one can get much information of flows by using particle image velocimetry (PIV). PIV has been developed to a very powerful tool for velocity filed measurements. There are a lot of articles on PIV applications. And a lot of algorithms for velocity field reconstruction have been proposed for the correlation and tracking analysis. According to the development of fast correlation algorithm and hardware, this technique should be applied to various flows in various engineering fields.

Basically, the main part of image processing in correlation-PIV is to analyze the correlation between two image patterns. In this calculation, the profile of image is more important rather than its intensity distribution. In this meaning, it is required to divide the flow image into sub-regions. Then the spatial resolution of the measurement is restricted by the interrogation spot size. Here, referring on the amount of image information, in the case of normal CCD camera (512x512 pixels and 8bits intensity resolution), the total amount is counted as 26 bits. Supposing that interrogation spot size is 32×32, 16×16 vectors or 32×32 vectors will be obtained by using a standard analysis. It is not important for correlation calculation that the dynamic range of image is 8 bits. It is one of merits of PIV that the expected results are not so sensitive on image intensity variation. Recent developments of PIV are characterized by keywords, such as high accuracy, high resolution, and 3D. In order to establish these technique, high performance devises for image recording with high density and wide dynamic range are required. The present study is concerned with the technique of three-dimensional velocity measurement.

There are some techniques for three-dimensional PIV. These are roughly separated into two categories. One is measurement of three-component of velocity in an observing plane. The other is measurement of velocity distribution in a full three-dimensional measurement volume. Stereoscopic PIV (Arroy and Greated (1991), Sinha and Kulman (1992), Prasad and Adrian (1992)) has been developed as the typical one of the former. Parallel light sheet method (Raffel et al. (1995)), color-coded light-sheet method (Brucker (1996)) and method of defocus image caused by out-of-plane particle displacement (Lee et al. (1997)) also give three-component of velocity in a measurement plane. On the other hand, three-dimensional particle tracking method using 2 or 3 CCD cameras (Doi et al. (1983)) is one of the fundamental techniques for whole-field velocity measurement. Holographic PIV (HPIV) (Dadi et al. (1991), Meng and Hussain (1991), Coupland and Halliwell (1992), Barnhart et al. (1994)) has recently been developed as a promising technique of whole field velocity measurement. The main goal of PIV technique might be that one can obtain time sequential data of three-components of velocity in full three-dimensional inspection volume. However, current systems are not yet a complete technique for this goal. We can get three-components of flow velocity in an inspected plane with stereoscopic-PIV system, but usually we can only get the two- dimensional information in the test section. Holographic-PIV gives us a complete three-dimensional velocity component in the test volume, but it is difficult to obtain a time sequential data. These techniques should be improved by using higher performance devices.

In the present study, a new technique of particle position measurement in depth direction by using gradational multi-color illumination system is proposed in order to obtain time sequential, three-dimensional velocity component in three-dimensional inspection volume. In a usual two-dimensional PIV or PTV system, a particle location is determined by particle-tracking algorithm or spatialy encoded method such as stereoscopy and defocus imaging. The intensity distribution of the image includes information of particle configuration, size, etc. The planar displacement of the particle within a short time interval δt is obtained by auto-correlation or cross correlation evaluation from these images. Thus, fundamentally, x, y coordinates of particle are determined from the particle image by correlation evaluation calculated by using image intensity pattern. In the present method, a three-dimensional test volume seeded with tracer particles is illuminated by intensity encoded two-color lights. The image of composite light scattered by particles is recorded by 3CCD (RGB) camera. The x, y coordinates of particles is directly determined from the particle image, and the depth in z-coordinate of each particle is determined by the intensity ratio of the decomposed-color-images. Fundamental characteristic of this method is demonstrated by reconstruction of a three-dimensional object placed in the test section, and simple flows seeded with tracer partcles are inspected by using this method.

2. Basic concept and Instrumentation

Figure 1 shows the schematic optical arrangement which is used in the present experiment. Argon-ion laser and He-Ne laser are used as two-color (blue and red) light sources. Both beams of the lasers are collimated by spatial filter and achromatic lenses. The output power of He-Ne laser is 30 mW, so the output of argon-ion laser is tuned as the same level as He-Ne laser. The diameter of collimated laser beam is about 50 mm. Using gradation wedge filter, the two collimated laser lights have linear gradation in z-direction, and its gradation is reverse to the other one. Gradation wedge is composed with two glass plates and filled with dyed water, so that the transmitted light intensity should be diminished exponentially. When the flow is seeded with tracer particles, the particle image is recorded by 3CCD camera and normal color camera.

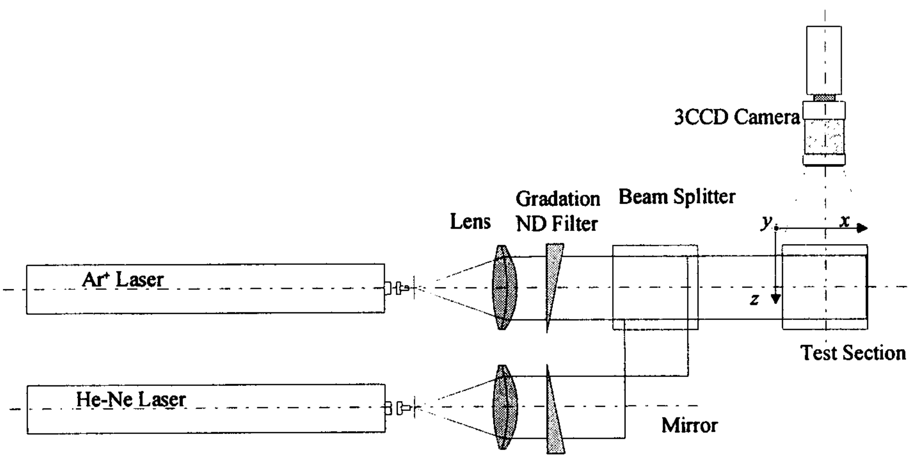


Fig.1 Optical instrumentation

The basic concept of the present method is demonstrated in fig.2. A mixed parallel plane light illuminates an object. The light scattered by it is detected by color CCD camera. If the intensity distributions of two incident beams, $I_R=I_R(x,y,z)$ and $I_B=I_B(x,y,z)$, are known, the intensity ratio of the scattered light I'_R/I'_B should be equal to the ratio, I_R/I_B. In general, when a map of I_R/I_B is completed by using suitable calibration procedure, the three-dimensional profile of the object can be reconstructed from the scattering intensity measured. In the simplest case when the intensity, I_R and I_B depend on only z, the ratio, I'_R/I'_B is only a function of z. In this case, the reconstruction is more easy. If the size of scattering object (particle) is much larger than the wavelength of illumination light, the ratio I'_R/I'_B does not depend on the size of the object.

In the present experiment, the image of test section is taken from the direction perpendicular to laser beam. The projected plane is determined by the image, and z-coordinate is determined by I'_R/I'_B. Of course, in more general case, if a suitable calibration is applied, the system that the measurement does not depend on the camera angle can be established.

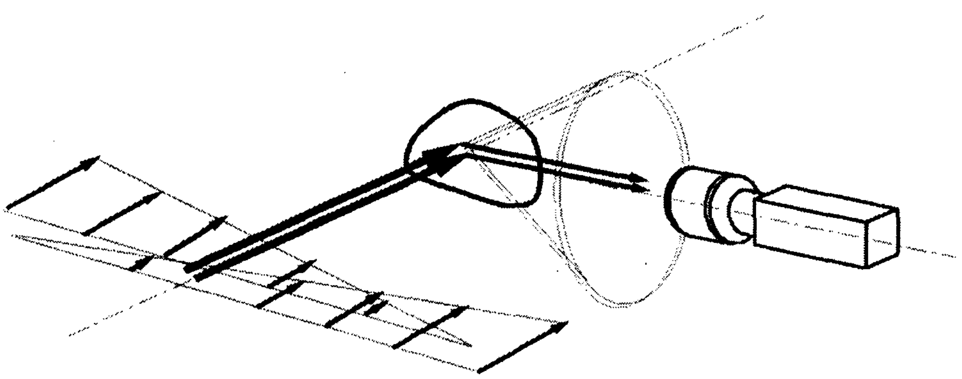
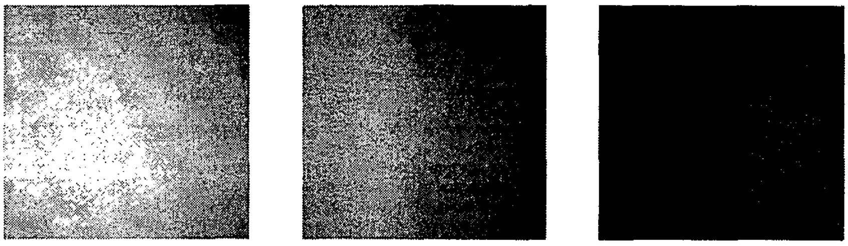


Fig.2 Basic concept of the measurement

3. Calibration procedure

For the calibration, a sheet of white paper is placed at the test section in the parallel to y-axis as a scattering plane. The paper is tilting 45 degrees in y-axis for the optical axis. The image is taken by color CCD camera and the color image is decomposed into R-G-B planes. Figure 3 shows calibration image maps. The image shown in fig.3 (a) is an original image of calibration plane, and (b) and (c) show decomposed images of (B+G) and R-planes, respectively. As the wavelengths of 488nm and 514nm are dominant in multi-modes oscillation of Ar-ion laser, superimposed (B+G) plane is adopted in the analysis. The intensity of (B+G)-plane, $I_{(B+G)}$ decreases with x, while I_R increases in R-plane. The averaged intensity is shown in fig.4. The ratio of I_R /$I_{(B+G)}$ can be assign to the position in z-directiion. Finally, a



(a) Mixed beam (b) (B+G) plane (c) R plane

Fig.3 Calibration planes

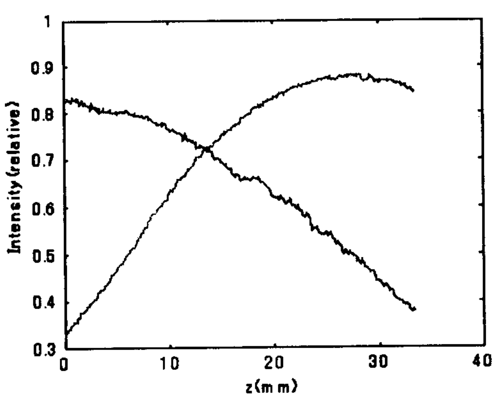


Fig.4 Intensity distribution of calibration plate

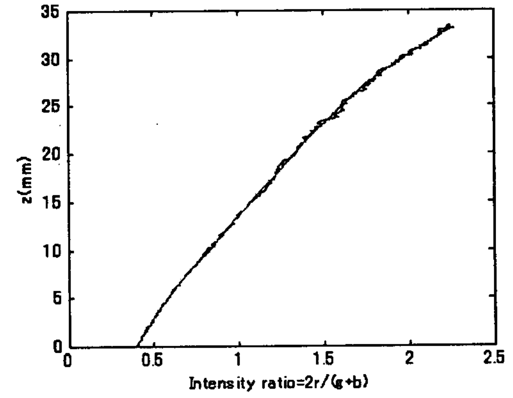


Fig.5 Calibration curve

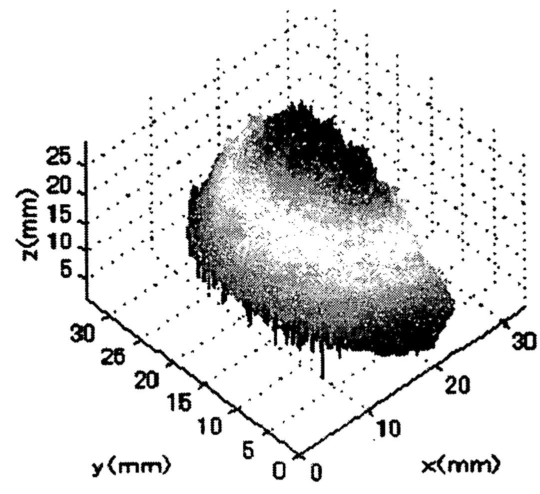


Fig.6 An image of the sphere

Fig.7 Reconstructed shpere profile

calibration curve is obtained as shown in fig.5. The experimental data are plotted in the blue line, and the red line shows polynomial curve fitted to these experimental data. By using the polynomial function in image processing, the z coordinate can be determined from intensity ratio at any (x, y) position.

Based on this calibration curve, a profile of a simple three-dimensional object is measured as a preliminary test. A ball of table tennis is placed at the center of test section. The recorded image is transferred to personal computer and analyzed by image processing tools. The original image of the sphere is shown in fig.6. The image is decomposed into R and (B+G) planes. Let $I_R=I_R(xylem)$ and $I_{(B+G)}=I_{(B+G)}(x, y)$ be the image functions of R-plane and (B+G) plane, respectively. The intensity ratio, $I_R/I_{(B+G)}$ gives us the z-coordinate of the sphere. The result of $I_R/I_{(B+G)}$ is shown in fig.7. The sphere profile is fairly reconstructed in this figure, but it includes to some extent error. This ambiguity is arisen by the coherency of laser light. As shown in fig. 6, laser speckle is observed, so that the image includes random noise. There are some optical means of removing the influence of speckle noise. A choice of incoherent light source should be a better option.

4. Flow measurements

Figure 8 shows the schematic view of flow measurement. A vessel filled with water seeded with tracer particles with mean diameter 100 μm is placed at the test section. Its size is 100mmx100mmx50mm. A half volume is illuminated by composed laser beam. The effective volume of the test section in the present analysis is 20mmx20mmx20mm. At first, simple displacement vectors of particles are measured

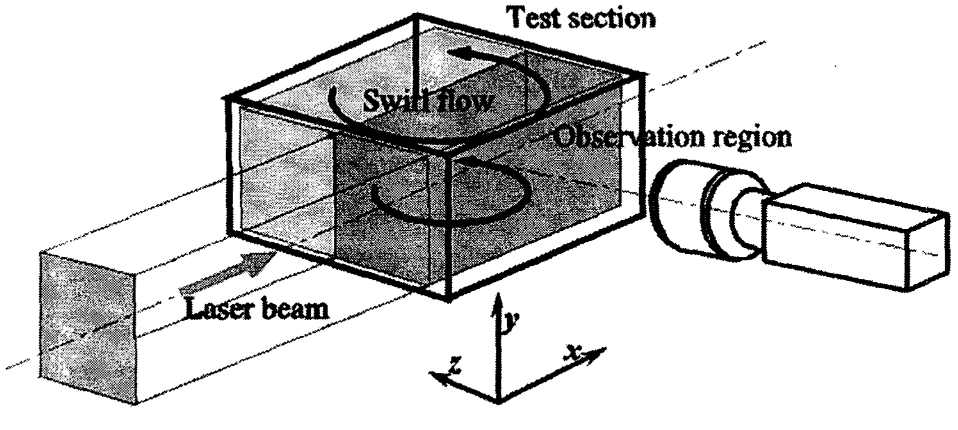


Fig.8 Schematic view of flow measurement

by this technique. The vessel is displaced to 1mm in z-direction. The images before and after the displacement are recorded and the three-dimensional displacement vector map is reconstructed. The matching of each particle image is carried out manually in this experiment as preliminary test. The example of particles image is shown in fig.9. Focus plane of the image is the center of illumination beam. The intensity $(I_R+I_{(G+B)})$ and the intensity ratio $(2I_R/I_{(G+B)})$ of focused and defocused particle images are shown in fig.10. The size of defocused image is expanded, but the intensity and the intensity ratio show the same tendency with these of focused image. The particle displacement vector map obtained is shown in fig.11, and it shows the fundamental feasibility of this method.

This method is also applied to a simple flow field. A weak circulation is added manually to the fluid in the vessel to generate a three-dimensional swirl flow as shown in fig.8. The flow is observed by a DV-camera. Video rate is normal 30 Hz but shutter speed is 1/8 sec. The recorded frames are transferred to a personal computer. The 270×270 pixels area for analysis is selected from the original image plane. Simple particle tracking procedure is applied to reconstruct three-dimensional velocity map. In order

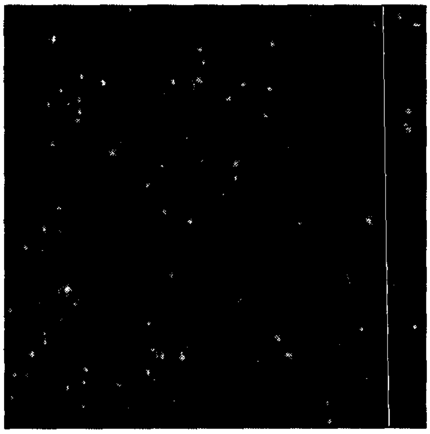
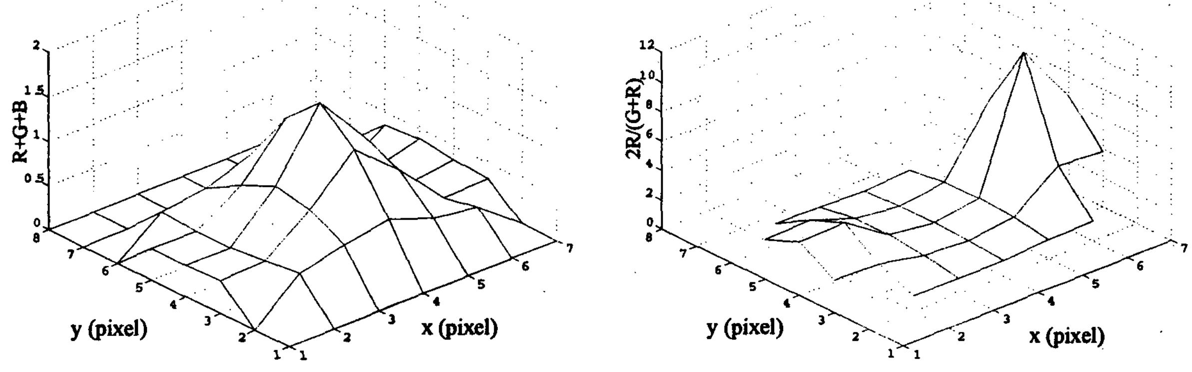


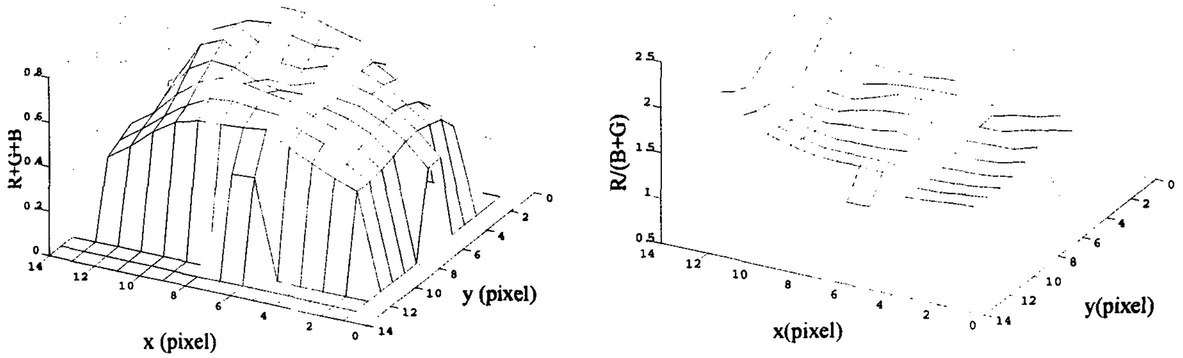
Fig.9 Particle images in the vessel.



(a-1) particle image intensity

(a-2) intensity ratio of R to (G+B)

(a) focused particle image



(b-1) particle image intensity (b-2) intensity ratio of R to (G+B)

(b) defocused particle image

Fig.10 Particle image intensity and intensity ratio of $I_R/I_{(G+B)}$

to determine the x and y coordinates of a particle, the center of particle image is calculated by averaging the particle intensity. In the present analysis, 50 particles were picked up from one plane. These are traced with time, and the intensity ratio of R to (G+B) is obtained at the image center of all particles. The result of tree-dimensional velocity vector map reconstructed by the procedure is shown in fig.12. It seems that many erroneous vectors include in the results. In order to improve this method, fundamental optical problems, such as laser speckle noise, angle dependence of Mie scattering, calibration procedure and so on, must be investigated in detail. Proper function encoding intensity of illumination lights must be considered. The image processing method used in this study is just prototype. A lot of sequence will be able to be proposed for the image processing in this method.

5. Conclusion

A new technique of three-dimensional velocity measurement has been proposed by using a two color encoded illumination system. This technique is advantageous in that only one camera is used to record the whole field information of fluid flow seeded with tracer particles, and particle position in z-direction can

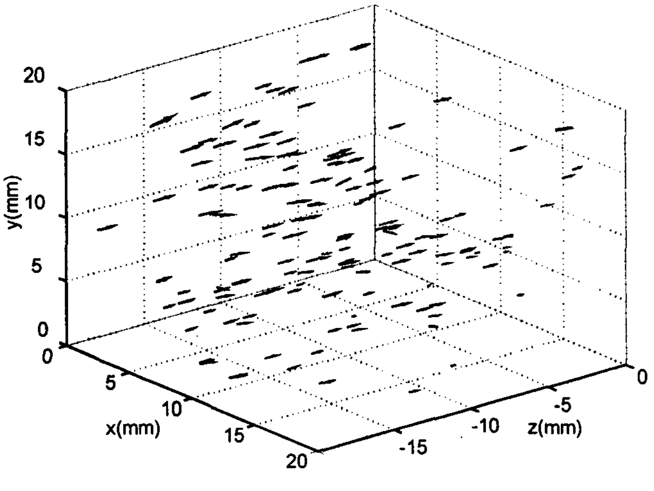


Fig.11 Three-dimensional displacement vector map

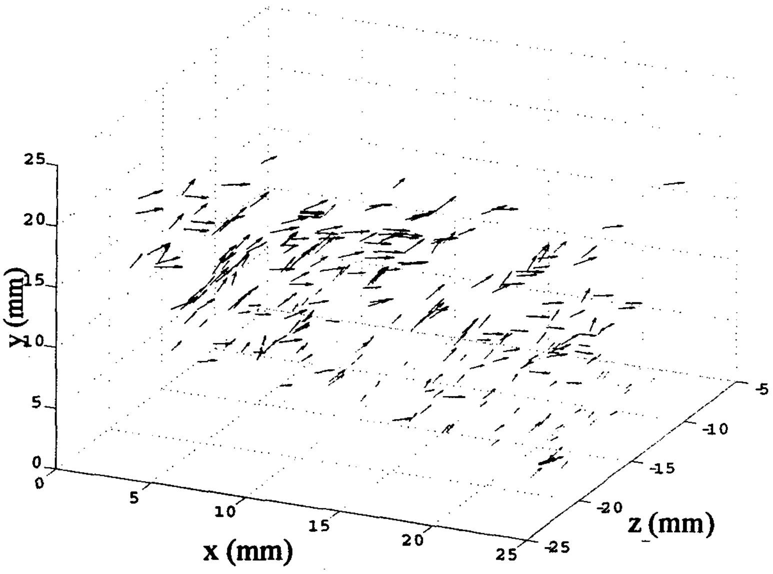


Fig.12 Three-dimensional velocity vector map

be determined by very simple algorithm. Preliminary profile detection for three-dimensional object was demonstrated. Velocity fields of simple flows were measured with the present technique. Although a certain error is included in the measured results, the results show a fair three-dimensional vector map. At the present stage, the accuracy of measurement with this method is not enough, however, it will be improved by resolving noise problem and by applying suitable method of calibration and image processing.

Acknowledgments

The authors thank for a great help in carrying out the present experiment to Mr. I. Shigematsu, who was a graduate school student of Saitama University.

References

Arroy, M.P. ; **Greated, C.A.** (1991) Stereoscopic particle image velocimetry, Meas. Scie. & Tech., 2, pp.1181-1186.

Barnhart, D.H.; **Adrian, R.J.**; **Papen, G.C.** (1994) Phase- conjugate holographic system for high-resolution particle image velocimetry, Appl. Opt., 33, pp.7159-7170.

Brucker, C.H. (1996) 3-D PIV via spatial correlation in a color-coded light-sheet, Exp. Fluids, 21, pp.312-314.

Coupland J.M.; **Halliwell N.A.** (1992) Particle image velocimetry: three-dimensional fluid velocity measurements using holographic recording and optical correlation. Appl. Optics, 31, pp. 1005-1007.

Dadi M.; **Stanislas M.**; **Rodriguez O.**; **Dyment A.** (1991) A study by holographic velocimetry of the behaviour of free particles in a flow, Exp. Fluids, 10, pp. 285-294.

Doi, J.; **Miyake, T.**; **Asanuma, T** (1983) Three-dimensional flow analysis by on-line particle tracking. Flow Visual. III, Wash. D.C., Hemisphere, pp.14-18.

Lee, W.K.; **Judge, L.S.**; **Burnett, M.**; **Udrea, D.D.**, **Bryanston-Cross, P.J.** (1997) Whole-field instantaneous 3D PIV meausement in air, Proc. SPIE, 3172, pp.551-560.

Meng, H.; **Hussain, F.** (1991) Holographic particle velocimetry: a 3D measurement technique for vortex interactions, coherent structures and turbulence, Fluid Dynamic Research, 8, pp.33-52.

Prasad A.K.; Adrian R.J. (1993) Stereoscopic particle image velocimetry applied to liquid flows, Exp. Fluids, 15, pp. 49-60.

Raffel M.; Gharib M.; Ronneberger O.; Kompenhans J. (1995) Feasibility study of three-dimensional PIV by correlating images of particles within parallel light sheet planes, Exp. Fluids, 19, pp. 69-77.

Sinha, S.K.; Kulman, P.S. (1992) Investigating the use of stereoscopic particle streak velocimetry for eswtimating the three-dimensional velocity field, Exp. Fluids, 12, pp.377-384.