106 Notes on Numerical Fluid Mechanics and Multidisciplinary Design (NNFM)

Imaging Measurement Methods for Flow Analysis

Results of the DFG Priority Programme 1147 "Imaging Measurement Methods for Flow Analysis" 2003–2009

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Preface

In 2003 the German Research Foundation established a new priority programme on the subject of "Imaging Measurement Methods for Flow Analysis" (SPP 1147). This research programme was based on the fact that experimental flow analysis, in addition to theory and numerics, has always played a predominant part both in flow research and in other areas of industrial practice. At the time, however, comparisons with numerical tools (such as Computational Fluid Dynamics), which were increasingly used in research and practical applications, soon made it clear that there are relatively few experimental procedures which can keep up with state-of-the-art numerical methods in respect of their informative value, e.g. with regard to visual-spatial analysis or the dynamics of flow fields. The priority programme "Imaging Measurement Methods for Flow Analysis" was to help close this development gap. Hence the project was to focus on the investigation of efficient measurement methods to analyse complex spatial flow fields. Specific cooperations with computer sciences and especially measurement physics were to advance flow measurement techniques to a widely renowned key technology, exceeding the classical fields of fluid mechanics by a long chalk.

The SSP-Research Programme, which was funded over a period of six years, was roughly divided into the subject areas of field measurement methods, surface measurement methods as well as flow measurement techniques based on micro electromechanical sensors (MEMS). These sub-areas were investigated by interdisciplinary research groups from the fields of flow mechanics (including users from applied engineering sciences), measurement physics and computer sciences (in the latter case involving methods for digital imaging and analysis). The objective of the individual tasks was to arrive at a meaningful "image" of the flow field, making it possible, for instance, to recognize coherencies in the physical flow and to assess model representations.

The articles on the individual projects combined in this book aim to provide a comprehensive overview of the research activities in the years 2003 to 2009. All papers submitted were thoroughly screened at first and subsequently presented to the Editor General of the NNFM series of publications. The editors wish to express

their gratitude to all authors concerned, the reviewers listed below as well as Prof. W. Schröder, the NNFM-Editor responsible, for their great and congenial collaboration.

Last but not least everyone involved would like to thank the German Research Foundation for funding the SPP1147 joint research project. Special thanks go to the respective staff of the German Research Foundation, particularly Dr. Lachenmeier, Dr. Meier as well as to Dr. Hillenherms (Ms) for the final phase of the project.

Berlin,
January 2009

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Coordinator of the SPP1147

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Principles of a Volumetric Velocity Measurement Technique Based on Optical Aberrations

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Abstract. In this contribution, a simple and robust three dimensional measurement technique for the determination of all velocity components is presented. As opposed to other techniques, only a single camera is required in order to calculate the particle positions in physical space. This is possible because the depth position of the particles is encoded using an optical aberration or wavefront distortion, called astigmatism. The astigmatism causes the particle images to have ellipse-like shapes. The length of the semi-major axis and the semi-minor axis depends on the depth wise position of the particle. It will be shown that this effect is well suited for extracting the particle positions. In the first section, an introduction is given and the measurement principle is shown in detail. Subsequently, the validation of the technique is illustrated by means of synthetically generated images. Finally, experimental results are presented and a conclusion is drawn.

1 Introduction

The measurement of the three velocity components in a volume is of interest for many fluid mechanics investigations. Therefore, different techniques with different advantages and drawbacks have been developed in recent years. One of these

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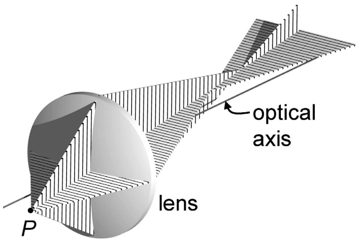
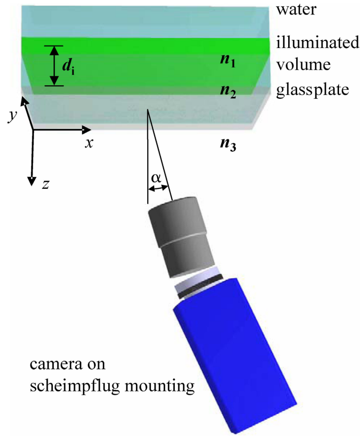
methods is the particle tracking velocimetry, which allows the determination of the velocities of single particles [14]. A drawback of this method is the large number of cameras which is required to determine the particle positions in physical space unambiguously and the limited depth of focus which restricts the measurement volume depth. Another technique is the scanning particle image velocimetry [4, 9], where the volume is scanned with thin light sheets in order to determine the velocities in these sheets. Occasionally the in-plane velocities are measured and the third velocity component is calculated by means of mass conservation. Due to the recording of many planes, the temporal sampling of the volume is reduced, which is why this method is only applicable to flows with large time scales (10 scanning sheets reduce the temporal resolution for the volume at least by a factor of 10). A benefit of this approach is the use of a light sheet as opposed to the other three dimensional methods which require volume illumination. Another method for the determination of the three velocity components in a volume is holographic PIV [2, 8, 11]. This method requires a record carrier with high capacity. Using an analog medium leads to the problem of a complicated recording and evaluation process. The application of a digital camera chip restricts the measurement volume size significantly because of the limiting pixel number. A relatively new approach is tomographic PIV [5, 6], where a reconstruction of the measurement volume by means of tomographic algorithms is done. Similar to PTV, 4 cameras are usually required to acquire the positions of the particles in space reliable and with sufficient accuracy. However, multiple camera systems are expensive and frequently not applicable due to limited optical access or problems associated with the calibration. Willert and Gharib [15] proposed a concept which solved most of the drawbacks of the discussed methods. Their approach is based on a single camera with a modified three hole-aperture which makes it possible to obtain three particle images from a single particle. The depth position of the particle can thus be gathered from the distances between the three images. Unfortunately, the modification of the aperture and the required laser power are drawbacks of this technique. In order to overcome these problems, the so called V3V system was developed by TSI, see [13]. Instead of an aperture with three holes, three separate cameras are used.

The 3D3C time-resolved measurement technique presented here requires a single camera as well, but no modification of the aperture is necessary [7]. A similar approach was applied to microfluidics in the past by [10, 12]. They put a cylindrical lens in the optical path which leads to a distortion of the particle images in dependence on their position in depth direction. This principle was also used by [1] to measure flow velocities in larger volumes. The effect caused by a cylindrical lens is similar to an optical aberration called astigmatism [3]. In Fig. 1(a) the principle path of rays is shown under the consideration of this effect. If a point light source P is not placed on the optical axis of a lens, there is no focal point in the image plane. Instead of one focal point, two focal lines with orthogonal orientations appear. Between these focal lines, the point light source produces an ellipse-like image. The size and shape of the particle image can be used to determine the three dimensional position of the particle in physical space.



(a) Astigmatism



(b) Principle of the experimental setup

Fig. 1 Astigmatism using a single lens and applied experimental setup

2 Measurement Principle

The astigmatism mentioned earlier hardly occurs if objectives are used because optical aberrations are corrected for in such a way that the aberrations are below the resolution limit of the CCD / CMOS sensors. The larger the distance of the light rays from the optical axis, the larger the optical aberrations. In order to obtain a well defined astigmatism, the specific setup shown in Fig. 1(b) is applied. A single camera mounted on a Scheimpflug adapter is aligned to the measurement volume at angle α. This angle leads in a combination with the refraction indices n_1, n_2 and n_3 to astigmatism. Three exemplary images are shown in Fig. 2 to illustrate the effect. Only a thin light sheet was used to illuminate the particles in this case. The light sheet was traversed about 6 mm towards the camera from image 1 to image 3. In the first recording, the particle images have an ellipse like shape with a small width and a large height. In the second image the width and height of the particle images are nearly equal and at the third position, the width of the particle images is much larger than their height. When the whole volume is illuminated, the positions of the particles in depth-direction can be determined by means of their orientation and shape.

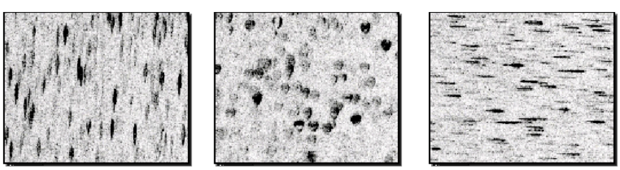


Fig. 2 Dependence of the particle image shape on the position in the measurement volume (only a thin sheet in the measurement volume is illuminated)

To estimate the positions of the particles in physical space, the following steps are required:

1. Calibration of the measurement volume by means of a traversed grid (similar to stereo PIV or other 3D3C Techniques)
2. Calibration by means of thin light sheets to determine the particle shape dependence on the position of the particle in the light sheet
3. Reconstruction of the particle position in physical space by means of the particle position on the chip, the particle shape, and the calibrations mentioned above.

2.1 Measurement Volume Size

The measurement volume size in the $x-$ and $y-$directions (defined in Fig. 1(b)) is mainly specified by the focal length of the objective and the distance of the objective from the measurement volume. The depth of the measurement volume depends on the angle α, the refraction indices n_1, n_2 and n_3, and the thickness of the glass plate. Furthermore, the distance d_i from the center of the measurement volume to the glass plate influences the measurement volume depth. If the glass plate is neglected ($n_1 = n_2$), the measurement volume depth assumes the size which is shown in Fig. 3. The calculation of this depth is done in the following way: A ray starts in the $x-z-$plane with angle α_0 from an arbitrarily positioned point light source near the measurement volume. Because intersections of rays must be calculated later, four additional rays are generated. Two rays (A_1 and A_2) are generated by rotating the initial ray around $\pm\mathrm{d}\alpha_0$ in the $x-z-$plane. Two additional rays (B_1 and B_2) are generated by rotating the initial ray around $\pm\mathrm{d}\alpha_0$ in the plane which is produced by the $y-$axis and the initial ray. The four rays are refracted at the intersection plane of water-air. Now the intersection points of the refracted rays A_1, A_2 and B_1, B_2 are determined for $\mathrm{d}\alpha_0 \rightarrow 0$. By means of this method, two virtual particle positions whose distance in the $z-$direction is assumed to be the measurement volume depth are calculated. The mid-point between the virtual particle positions in the $z-$direction is d_i.

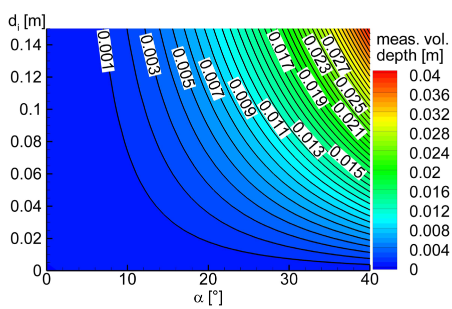


Fig. 3 The dependence of the measurement volume depth on the angle α and the distance d_i of the center of the measurement volume to the boundary ($n_1 = 1.33$, $n_2 = n_3 = 1.0$)

2.2 Calibration of the Measurement Volume

The measurement volume is viewed at the angle α leading to the distortion of the grid which is aligned parallel to the light sheet. In addition, the distortion depends on the position in the measurement volume. For this reason it is necessary to make a 3D calibration to convert the coordinates in the image plane to coordinates in physical space:

$$
\begin{aligned}
f(x[\mathrm{m}]) &= f(x[\mathrm{px}], y[\mathrm{px}], z[\mathrm{m}]) \\
f(y[\mathrm{m}]) &= f(x[\mathrm{px}], y[\mathrm{px}], z[\mathrm{m}]) \\
f(z[\mathrm{m}]) &= f(x[\mathrm{px}], y[\mathrm{px}], z[\mathrm{m}])
\end{aligned} \tag{1}
$$

A grid is placed in the measurement volume and recorded at several positions. The intersections of the grid lines are determined by means of cross correlation of the calibration images with an artificially generated cross. The line thickness of the cross in the $x-$ and $y-$directions is entered manually for each calibration position because the astigmatism causes a different line width and height for each position of calibration target in $z-$position.

2.3 Particle Image Fitting

The fitting of the particle images is essential for the presented measurement technique because the particle position is directly associated with the particle image shape. In Fig. 4 the measurement uncertainty in the $z-$direction is shown as a function of the particle $z-$position and the uncertainty in determining the particle image width and height. The measurement volume depth is assumed to be 1 and the uncertainty is the standard deviation given in percent of the measurements volume depth. The calculation was done for particle images with width and height between 1 px and 20 px depending on the $z-$position of the particle. Applying a larger range, the measurement error is reduced.

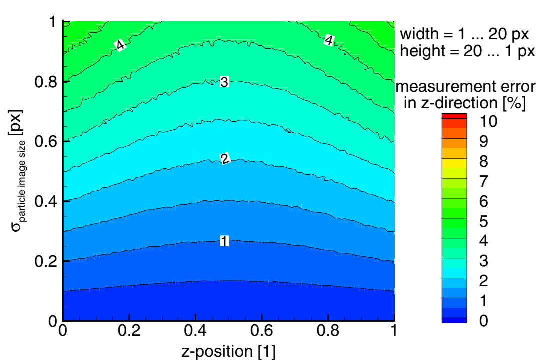


Fig. 4 Dependence of the measurement uncertainty in the $z-$direction in percent of the measurement volume depth on the $z-$position and the uncertainty in determining the particle image width and height (particle image width and height vary between 1 px and 20 px in dependence on the $z-$position)

The setup causes a wave front deformation which results in the distorted particle images. The size of the particle images in the $x-$ and $y-$directions depends on the light intensity which is scattered by a particle. However, if the particle image intensity distribution is assumed to be 2D Gaussian, the particle image width and height defined by the e^{-2} intensity do not depend on the intensity of a particle in physical space. The scattered light intensity of a particle depends strongly on the particle size, the index of defraction, the stability of the laser, and the position of the particle in the light sheet. Due to the fact that the particle image intensity distribution is not a 2D Gauss function and the particle image width and height therefore depend on the particle intensity, the particle shape is defined here by the ratio of the particle image width to the particle image height. This ratio is nearly independent from the intensity of the scattered light of a particle.

The determination of the particle image width and height is performed in the following way: First, the pixels which might belong to a particle image are determined by means of a median filter. Then, the segmentation takes place (see Fig. 6) where neighboring pixels are assigned to particle images. In the next step, the pixels of a particle image in a rectangular area around the particle image are applied to fit a 2D Gauss function:

$$f(x,y) = a_1 \cdot \exp\left(-8.0 \cdot \frac{(a_2 - x)^2}{a_3} - 8.0 \cdot \frac{(a_4 - y)^2}{a_5}\right) + a_6 \tag{2}$$

The fitting is done by means of a Gauss-Newton method. In order to get a result for the fitting coefficients which does not depend on the initially-chosen rectangular pixel area, 4 iterations are done. In each iteration the width and height of the area are chosen at twice the width and height of the particle image (width = $\sqrt{a_3}$, height = $\sqrt{a_5}$). A reconstructed particle image is shown in Fig. 6. Actually, the particle images do not have a gaussian intensity distribution which often leads to the problem that the fitting does not work very well (lock in of the fitting-function to the pixels with a high intensity), see Fig. 5 on the left hand side. Therefore, the autocorrelation of the particle image with the rectangle determined earlier is performed. Again, four iterations for the adaption of the rectangle are done. The correlation peak is much smoother than the intensity distribution of the particle image that makes the estimation of the particle image width and height easier, see Fig. 5 on the right hand side. So far, the particle image width is assumed to be the width of the normalized correlation peak at a correlation amplitude of 0.5. The particle image height is determined in a similar way.

A drawback of the autocorrelation method is that one gets only the particle image width and height so that the particle position is given by the parameters a_2 and a_4 from the Gaussian fit. The reconstructed particle image is shown in Fig. 6. The $z-$positions of the two particles are similar because only a thin light-sheet was used for the illumination. The Gaussian fit leads to a ratio of the particle image width to the particle image height of 3.55 for the upper, and 2.95 for the lower particle image. By applying the approach with the autocorrelation, one gets ratios of 3.35 and 2.92, which is in much better agreement. The ratio 3.35 leads to a z-position of 14.527 mm and the ratio 2.92 leads to a z-position of 14.145 mm.

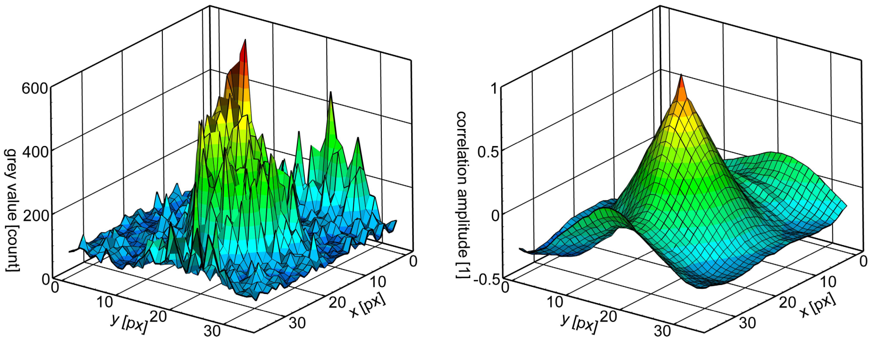


Fig. 5 Original particle image (left hand side) and autocorrelation plane (right hand side)

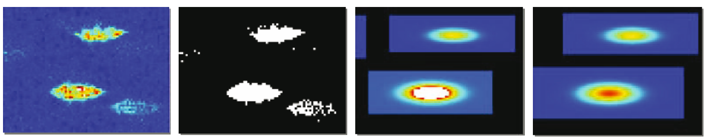


Fig. 6 Original particle image, segmented particle image, reconstructed particle image with parameters from a Gaussian fit (width/height upper particle = 3.55; width/height lower particle = 2.95) and reconstructed particle image with parameters from autocorrelation (width/height upper particle = 3.35; width/height lower particle = 2.92)

2.4 Calibration with Particle Images

Due to the astigmatism, the particle image shape depends on the positions of the particles in the depth direction (z), as pointed out before. In addition, the particle image shape varies in the $x-$ and $y-$directions. For this reason, a calibration

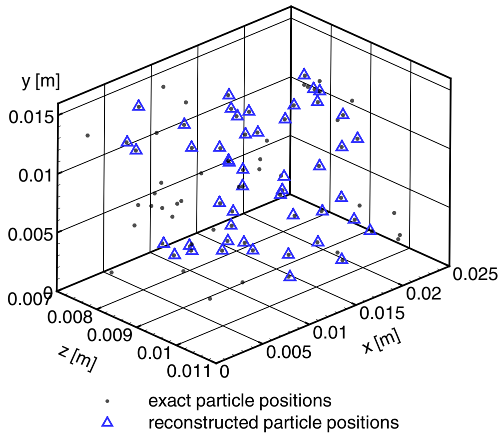
$$f(x[\mathrm{px}], y[\mathrm{px}], shape) = z[\mathrm{m}] \quad (3)$$

is necessary which maps the particle position and shape unambiguously. Therefore, the measurement volume is scanned with light sheets which are as thin as possible and many images are recorded at every light sheet position. The particle images are extracted and fitted as mentioned in section 2.3, and for each particle image the shape parameter is calculated. This is done for the whole volume. With these extracted particle images the coefficients of the 4th order rational calibration function are determined by means of the Levenberg-Marquardt method.

3 Validation

In order to validate the presented measurement technique, a simulation software for the generation of synthetic images was developed. Due to the implementation of the ray tracing technique, the software allows the simulation of astigmatism. The

Fig. 7 Comparison of the exact and the reconstructed particle positions



generation of calibration grids is also possible so that the whole measurement procedure can be emulated. In Fig. 7 a result of the synthetic simulation is shown. The black points indicate the exact particle positions which are known due to the simulation. The blue triangles are the particle positions which have been calculated by means of the method presented. It can be seen that the agreement between these positions is quite good. Presently, the error (RMS) of the particle locations is $2.6 \cdot 10^{-5}$ m. In the experimental setup the particle positions are not known. However, examinations on the accuracy can still be done. The calibration with particle images mentioned in section 2.4 is applied to experimentally recorded images in the following. In this experiment the angle α was 30° and the measurement volume depth $\delta z = 15$ mm. In Fig. 8 on the left-hand side the particle images extracted from the calibration recordings are shown. The $x-$ and $y-$positions in the image coordinate system and the exact $z-$position in physical space are known. The contour color

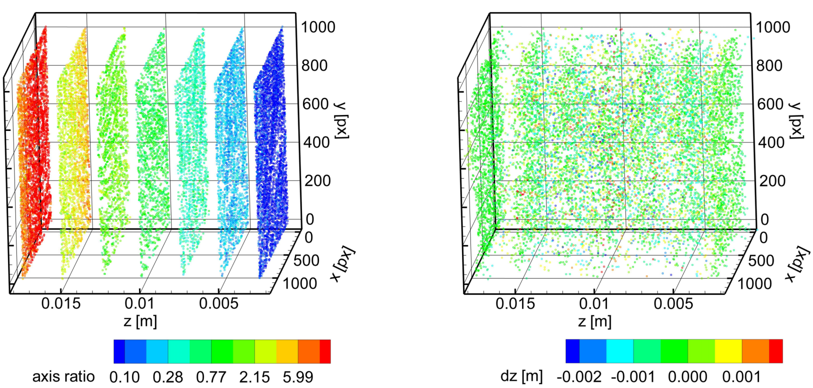


Fig. 8 The dependence of the axis ratio on the particle position (left-hand side) and the deviation of the calculated z-positions to the exact z-positions (right-hand side)

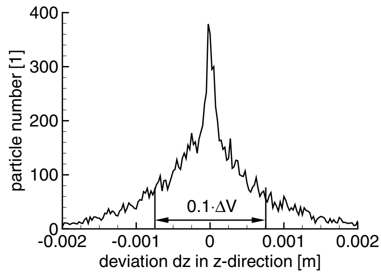


Fig. 9 PDF of the deviations in z-direction shown in Fig. 8 on the right-hand side

indicates the axis ratio (particle image width / particle image height). This data is used to calculate the coefficients of the calibration function for the particle images. The $z-$position can now be reconstructed by means of the positions $x\,[\mathrm{px}]$, $y\,[\mathrm{px}]$ and the axis ratio. This is given in Fig. 8 on the right-hand side where the contour color indicates the deviation of the calculated $z-$position to the exact $z-$position. The PDF of this field is shown in Fig. 9. Without any postprocessing, the standard deviation in the $z-$direction is 0.81 mm (5.4 % of the measurement volume depth). It can be seen that there is a clear peak at the position of 0 mm deviation in the $z-$direction which means that the presented method is free of systematic errors.

4 Determination of the Flow Velocity

In the last sections the determination of the particle positions in physical space by means of astigmatism has been explained. However, the goal of the presented technique is the determination of the three velocity components in a volume. There are mainly two possibilities to do this. One possibility is a three dimensional correlation, similar to the PIV interrogation. Similar to tomographic PIV, interrogation volumes must be applied for the evaluation. Another possibility for the determination of the particle displacements is the application of a particle tracking algorithm. The uncertainty in the displacement determination will be larger than for the correlation approach but the spatial resolution will be much better. Further investigations will show the advantages and drawbacks of each method.

5 Conclusion and Outlook

The principle of a measurement technique for the determination of all three velocity components in a three dimensional volume with only a single camera was shown. This is of interest for many applications with limited optical access like 3D-μ-PIV or the internal flow of a motor. μ-PIV requires a different calibration approach than the one with thin light-sheets described here, because the minimum thickness of light-sheets is limited. Therefore, particles aligned on a target will be moved by means of a micro-positioning system.

Further benefits of the measurement technique are the alignment and the calibration which are very easy with a single camera. The measurement uncertainty of the particle position in depth direction is approximately 5.4 % of the measurement volume depth so far. In the future, more suitable functions for fitting the particle images will be examined to increase the accuracy. It is assumed that this leads to an uncertainty in the $z-$direction of approximately 2 %. In addition, a postprocessing will be applied once the displacement of the particles is determined. It is assumed that this will eliminate particles whose $z-$positions have been found to be inaccurate.

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References

1. Angarita-Jaimes, N., McGhee, E., Chennaoui, M., Campbell, H.I., Zhang, S., Towers, C.E., Greenaway, A.H., Towers, D.P.: Wavefront sensing for single view three-component three-dimensional flow velocimetry. Exp. Fluids 41, 881–891 (2006)
2. Barnhart, D.H., Adrian, R.J., Papen, G.C.: Phase conjugate holographic system for high resolution particle image velocimetry. Appl. Opt. 33, 7159–7170 (1994)
3. Born, M., Wolf, E.: Principles of Optics. Pergamon Press, Oxford (1980)
4. Brücker, C.: Digital-Particle-lmage-Velocimetry (DPIV) in a scanning light-sheet: 3D starting flow around a short cylinder. Exp. Fluids 19, 255–263 (1995)
5. Elsinga, G.E., Scarano, F., Wieneke, B., van Oudheusden, B.W.: Tomographic particle image velocimetry. Exp. Fluids 41, 933–947 (2006)
6. Hain, R., Kähler, C.J., Michaelis, D.: Tomographic and time resolved PIV measurements on a finite cylinder mounted on a flat plate. Exp. Fluids 45, 715–724 (2008)
7. Hain, R., Kähler, C.J.: Single camera volumetric velocity measurements using optical aberrations. In: 12th International Symposium on Flow Visualization, Göttingen, Germany, Septermber 10-14 (2006)
8. Hinsch, K.D.: Holographic particle image velocimetry. Meas. Sci. Technol. 13, R61–R72 (2002)
9. Hori, T., Sakakibara, J.: High-speed scanning stereoscopic PIV for 3D vorticity measurement in liquids. Meas. Sci. Technol. 15, 1067–1078 (2004)
10. Pin Kao, H., Verkman, A.S.: Tracking of Single Fluorescent Particles in Three Dimensions: Use of Cylindrical Optics to Encode Particle Position. Biophys. J. 67, 1291–1300 (1994)
11. Pu, Y., Meng, H.: An advanced off-axis holographic particle image velocimetry (HPIV) system. Exp. Fluids 29, 184–197 (2000)
12. Ragan, T., Huang, H., So, P., Gratton, E.: 3D Particle Tracking on a Two-Photon Microscope. J. Fluorescence 16, 325–336 (2006)
13. TSI Incorporated. V3V Volumetric 3-Component Velocimetry System, September 13th (2008), `http://www.tsi.com/en-1033/products/2350/v3v.aspx`
14. Virant, M., Dracos, T.: 3D PTV and its application on Lagrangian motion. Meas. Sci. Technol. 8, 1539–1552 (1997)
15. Willert, C.E., Gharib, M.: Three-dimensional particle imaging with a single camera. Exp. Fluids 12, 353–358 (1992)