Digital-Particle-Image-Velocimetry (DPIV) in a scanning light-sheet: 3D starting flow around a short cylinder

Ch. Brücker

Abstract Scanning-Particle-Image-Velocimetry Technique (SPIV), introduced by Brücker (1992) and Brücker and Althaus (1992), offers the quantitative investigation of three-dimensional vortical structures in unsteady flows. On principle, this technique combines classical Particle-Image-Velocimetry (PIV) with volume scanning using a scanning light-sheet. In our previous studies, single scans obtained from photographic frame series were evaluated to show the instantaneous vortical structure of the respective flow phenomena. Here, continuous video recordings are processed to capture also the temporal information for the study of the set-up of 3D effects in the cylinder wake. The flow is continuously sampled in depth by the scanning light-sheet and in each of the parallel planes frame-to-frame cross-correlation of the video images (DPIV) is applied to obtain the 2D velocity field. Because the scanning frequency and repetition rate is high in comparison with the characteristic time-scale of the flow, the evaluation provides a complete time-record of the 3D flow during the starting process. With use of the continuity concept as described by Robinson and Rockwell (1993), we obtained in addition the out-of-plane component of the velocity in spanwise direction. This in view, the described technique enabled the reconstruction of the three-dimensional time-dependent velocity and vorticity field. The visualization of the dynamical behaviour of these quantities as, e.g., by video, gave a good impression of the spanwise flow showing the "tornado-like" suction effect of the starting vortices.

1 Introduction

The major aim of recent development in experimental flow measurement techniques is to offer a tool for quantitative whole-field studies of three-dimensional unsteady flows. The increasing success gives the chance for experimentalists to investigate these flow types by means of their three-dimensional structure and their time-dependent development as well, such as, e.g., the distribution of quantities like the vorticity or shear-rate. Single probe techniques like LDA (Laser-Doppler-Anemometry) cannot tackle those flow problems. Nowadays, the increasing availability of modern computers and image-processing-techniques has allowed the widespread application of more-dimensional methods like the Particle-Imaging-Techniques PIV (Particle-Image-Velocimetry) or PTV (Particle-Tracking-Velocimetry) in experimental flow studies (see the reviews from Adrian (1991) and Gad el Hak (1988)). These techniques are pushing forward the experimental investigations of complex flows and their understanding.

In classical 2-D PIV, the flow, seeded with small tracer particles, is illuminated in a small light-sheet that is arranged in the direction of the prevailing velocity. By a multieposure or multiframe-technique, the approximate instantaneous 2-D component of the velocity field within the light-sheet can be obtained from the displacement of the particle images or the patterns of their local clusters. Using a high particle density and correlation methods one yields a dense velocity distribution from which the spatial derivatives of the velocity components can be obtained within certain accuracy. This allowed experimentalists to evaluate the instantaneous in-plane distribution of vorticity or shear-rate. For those reasons this technique was very welcome. However, it yields the information only in a single, stationary slice in the flow (the plane of the light-sheet) and the evaluation of vorticity or shear-rate is restricted only to the component directed out of the light-sheet plane. This is one reason why many approaches were made to extend the classical PIV-technique to more dimensions. As summarized by Meng and Hussain (1991) "the need for experimental techniques which can resolve vorticity fields in space and time cannot be emphasized enough."

The common methods offering the extension of PIV to a whole-volume technique are the well-known holography or alternatively, a multiple camera system with different viewing angles. As shown in a recent article from Meinhart et al. (1994), holographic PIV (HPIV) enables the measurement of the order of $10^5$ instantaneous velocity vectors in a typical flow volume of $100 \times 100 \times 100$ mm$^3$ (the flow was recorded on holographic plates). This technique, however, was made applicable only by using an expensive optical environment and implementations of large computational power using parallel array processors. To obtain also the temporal information in complex flows, Weinstein and Beeler (1987) and Meng and Hussain (1991) suggested a holographic movie technique. They showed that holocinematographic PIV offers a great potential but needs a complex and expensive setup for recording, hologram reconstruction and data evaluation if one wants to use its potential.
Three-dimensional Particle-Tracking-Velocimetry (3D PTV) or Particle-Streak-Velocimetry are more convenient whole-volume PIV techniques based on multiple camera systems, where individual particles are tracked in space as they move along with the observed flow. Due to the nature of projection of a 3D volume onto planes, certain restrictions to the particle size and number density exist to avoid image overlap. Recent results of 3-D PTV using a multiple CCD camera system demonstrated, that the volumic distribution of vorticity cannot be obtained without remarkable errors (see Sinha and Kuhlman (1992)). A usual number of vectors achieved in the 3-D volume of interest is about a few thousand which is the same as one obtains using cross-correlation DPIV within a single light-sheet (depending on the resolution of the recording devices, see also the discussion of Prasad and Adrian (1993) for the optical PIV counterpart). Therefore, the effective spatial resolution of the vectors in 3-D PTV is always lower compared to the one in a light-sheet plane using DPIV. Thus the profit of 3-D PTV is questionable in flows, where the vorticity is one quantity of main interest, as also noted by Meng and Hussain (1991). Its potential, however, is evident in such cases where the Lagrange particle paths are of particular interest as, e.g., in transport phenomena or biomedical applications.

2 Whole-volume PIV by conventional PIV and a scanning light-sheet

The dilemma of the insufficient resolution of 3-D PTV for determination of the 3D vorticity field can be circumvented using PIV in combination with a scanning light-sheet as introduced by Brücker (1992) and Brücker and Althaus (1992). Since the light-sheet technique is conserved (although the light-sheet is not stationary but scanning through the volume) a high seeding density can be used and, therefore, a high spatial vector distribution is achievable that allows a reliable determination of the vorticity. The scanning light-sheet continuously samples the flow in depth in successive planes in each of which the 2D velocity field can be evaluated by cross-correlation PIV. Especially in such flows, where the vorticity vector has a more or less preferred orientation, its mean component can be obtained quasi-instantaneous in successive “cuts” through the flow field. This enables the volumic reconstruction of the instantaneous vorticity distribution as demonstrated by Brücker and Althaus (1992) on the phenomenon of vortex breakdown.

Beyond the measured in-plane velocity components, the concept of continuity (Robinson and Rockwell (1993)) enables, in principle, the determination of the out-of-plane component from 2-D velocity fields in parallel planes as shown by Robinson and Rockwell in a numerical simulation of PIV for generic vortical flows. One may also use a two-camera system as usually applied for 3D PIV (see Prasad and Adrian (1993) or Westerweel and Nieuwstadt (1991)) for direct measurement of the out-of-plane component in the scanning light-sheet, see Brücker (1995). In conclusion, the total number of achieved velocity vectors in space using SPIV and digital cross-correlation technique is about the number \( n_x \) of planes larger than in a single plane which allows the quasi-instantaneous measurement of about \( 10^4 \)–\( 10^5 \) vectors in space (dependent on the camera resolution and the number \( n_z \) of planes). Thus, the described SPIV technique can be viewed as a lowcost and more practical alternative to holocinematographic PIV for temporal studies of vortical structures in low Reynolds number flows.

A similar concept termed “multiple light sheet holography” was presented later by Hinsch (1993). In this approach, he used a stationary arrangement of four staggered parallel light-sheets in which the flow was double-exposed and recorded on holographic plates. Although this technique provides the instantaneous flow field simultaneously in several parallel cuts through the flow field, so far the technique is limited to only a few light-sheets (they gained in maximum four planes, results are only given for two planes) which additionally had to be separated by a certain amount (for the reasons see Hinsch (1993)). In contrast, SPIV allows application of conventional video or cinematographic recording and, depending on the optical scanning system, a close spacing of the successive light-sheets. Therefore continuous time-records of 3D unsteady flows can easily be obtained and evaluated.

In this article, SPIV was applied to the 3D unsteady starting flow around a circular cylinder using Digital-Particle-Image-Velocimetry (DPIV) and conventional video recording in combination with a rapid scanning light-sheet. It is demonstrated, that this technique yields the velocity throughout a complete volume as a function of time. From a technological point of view, the current maximum video image acquisition rate of 25 Hz limits the application of the video technique here to a low speed flow. However these limitations are more of technological nature rather than a conceptual one. Certainly, high-speed cinematography for SPIV is applicable, too, until high-speed, high-resolution digital video systems become more readily available and less costly.

2.1 Scanning light-sheet optics

The scanning technique will be explained here by means of the scanning system used in the present experiments, see Fig. 1 (a discussion of several light-sheet scanning methods for

![Fig. 1. Flow channel and optical set-up for the light-sheet scanning method](image-url)