3-D Scanning-Particle-Image-Velocimetry: Technique and Application to a Spherical Cap Wake Flow*

CH. BRÜCKER
Aerodynamisches Institut, RWTH Aachen, Templergraben 55, 52062 Aachen, Germany

Received 30 August 1995; accepted in revised form 10 April 1996

Abstract. A 3-D time-resolving and whole-volume Digital-Particle-Image-Velocimetry (DPIV) technique based on the concept of a scanning light-sheet is presented and applied here to the 3-D transient wake phenomena in the spherical cap wake flow. The technique uses a scanning light-sheet for rapid sampling of the flow in depth and a two-camera recording system for stereoscopic 3-D DPIV. Application of a correlation technique in combination with a calibration yields, aside from the correct in-plane displacement, also the out of plane component and thus the total velocity vectors within the planes of the scanning light-sheet. With a high scanning rate in comparison to the characteristic time scales the method provides the 3-D velocity field in space and time. Through the use of conventional video-techniques the temporal evolution of the complete velocity and vorticity field can be obtained quantitatively from experiments. This is demonstrated for the 3-D starting flow around a spherical cap at Re = 300. During the starting process, the flow in the wake evolves into a spherical vortex ring where the velocity distribution is very close to the theoretical solution of the Hill-type vortex. Later on, the Hill-type vortex ring deforms and the flow changes from a rotational symmetric stage to a planar symmetric flow with a double-threaded vortical structure which consists of two counter-rotating streamwise vortices similar to the ones observed in sphere wake flow.

Key words: 3-D PIV, scanning light sheet, spherical cap wake, sphere wake, Hill-vortex, transitional flow

1. Introduction

The major aim of recent developments in experimental flow measurement techniques is to offer a tool for quantitative whole-field studies of three-dimensional unsteady flows. The increasing success allows experimentalists to investigate these flows with regard to their three-dimensional structure and their time-dependent development as well, such as, the distribution of quantities like the vorticity and shear-rate. As summarized by Meng and Hussain [1] "the need for experimental techniques which can resolve vorticity fields in space and time cannot be emphasized enough." Nowadays, the availability of large computing power and image-processing-techniques has allowed the widespread application of multi-
dimensional methods like Particle-Image-Velocimetry (PIV) in experimental flow studies (see, e.g., [2]).

In classical 2-D PIV, the flow, seeded with small tracer particles, is illuminated in a thin light-sheet that is arranged in the direction of the prevailing velocity. By a multiexposure or multiframe-technique, the approximate, instantaneous 2-D components 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. 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 to only one component (for the vorticity, 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, for a recent review see Hinsch [3].

The common methods offering the extension of PIV to a whole-volume technique are the well-known holography or stereoscopy. Among others, Meng and Hussain [1] suggested a holographic movie technique for the study of complex flows in space and time but they could not present detailed results. In general, holocinematographic PIV offers a great potential; however, until today in practice it requires a complex and expensive setup for recording, hologram reconstruction and data evaluation.

Three-dimensional Particle-Tracking-Velocimetry (3-D PTV) or Particle-Streak-Velocimetry are more convenient whole-volume PIV techniques based on multiple camera systems. In this case individual particles are tracked in space as they move along with the observed flow. Due to the nature of projection of a 3-D 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 significant errors (see [4]). This is on the one hand due to the low spatial resolution achievable with PTV and on the other hand because of the higher errors in determination of the particle's position and their displacement using centroid techniques. Thus the use of 3-D PTV is questionable in flows, where the vorticity is one quantity of main interest, as also noted by Meng and Hussain [1].

The dilemma of the insufficient resolution of 3-D PTV for determination of the 3-D vorticity field can be resolved by using PIV in combination with a scanning light-sheet which is called "Scanning-Particle-Image-Velocimetry (SPIV)" in the following. This method as introduced by Brücker [5] and Brücker and Althaus [6] extends the spatial resolution of PIV into the depth component by continuously scanning the light-sheet through the volume during the measurements. 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,