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Particle Image Velocimetry in Aerodynamics: Technology and Applications in Wind Tunnels

Kompenhans, J.*1, Raffel, M.*1, Dieterle, L.*1, Dewhirst, T.*1, Vollmers, H.*1, Ehrenfried, K.*1, Willert, C.*2, Pengel, K.*3, Kähler, C.*1, Schröder, A.*1 and Ronneberger, O.*1

*1 Institut für Strömungsmechanik, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Bunsenstraße 10, D-37073 Göttingen, Germany.
*2 Institut für Antriebstechnik, DLR, Köln, Germany.
*3 Deutsch-Niederländischer Windkanal (DNW), Emmeloord, The Netherlands
e-mail: juergen.kompenhans@dlr.de

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***Abstract*:** Particle image velocimetry (PIV) is increasingly used for aerodynamic research and development. The PIV technique allows the recording of a complete flow velocity field in a plane of the flow within a few microseconds. Thus, it provides information about unsteady flow fields, which is difficult to obtain with other experimental techniques. The short acquisition time and fast availability of data reduce the operational time, and hence cost, in large scale test facilities. Technical progress made in the last years allowed DLR to develop a reliable, modular PIV system for use in industrial wind tunnels. The features of this system are summarized and results of recent PIV applications are presented.

***Keywords*:** particle image velocimetry, PIV, industrial wind tunnels, aerodynamics, unsteady flow fields.

1. Introduction

Over the past decade particle image velocimetry (PIV) has matured from its developmental stage to a reliable whole field flow measurement technique and now finds uses in a continuously broadening range of applications. This of course made a number of special implementations of the PIV technique necessary to suit the needs of many different fields such as biological research or turbomachinery, for instance. An especially important field of PIV applications is that of industrial aerodynamic research. PIV systems for the investigation of air flows in wind tunnels must be capable of recording low speed flows (e.g. flow velocities of less than 1 m/s in turbulent boundary layers) as well as high speed flows with flow velocities exceeding 500 m/s (e.g. supersonic flows with shocks). Flow fields above solid, moving, or deforming models in aerodynamics are usually associated with complex three dimensional flow structures of different length and time scales, which must be properly resolved by the PIV technique. The application of PIV in large, industrial wind tunnels poses a number of special problems:

- large observation areas,
- large observation distances between camera and light sheet,
- time constraints in the setup of the PIV system,
- strict safety requirements for laser, seeding, turbine or helicopter simulator and
- high operational costs of the wind tunnel.

In spite of these stringent requirements, the PIV technique is very attractive in modern aerodynamics research because it helps in the understanding of unsteady flow phenomena such as shear and boundary layers, wake vortices, and separated flows above models at high angle of attack. PIV enables spatially resolved measurements of the instantaneous velocity field within a very short time and allows the detection of large and small scale spatial structures in the flow. The PIV method can further provide the experimental data necessary to the validation of an increasing number of high quality numerical flow simulations. For this purpose carefully designed experiments with well known boundary conditions have to be performed in close cooperation with those scientists doing the numerical simulations. To allow a comparison with the numerical results, the experimental data of the flow field must possess high resolution in both space and time which is a requirement satisfied to a great extent by the PIV method, especially with regard to obtaining information about unsteady flow fields.

2. Experimental Setup for Particle Image Velocimetry for Application in Wind Tunnels

2.1 General

Adrian (1991) and Hinsch (1993) give detailed descriptions of various implementations of the PIV method which have been developed during the past 15 years. PIV systems, as utilized for flow field investigations in wind tunnels, have been described by Willert et al. (1996) and Raffel et al. (1998a).

The most widespread implementation of the PIV method (standard 2C-2D PIV) images seeding particles suspended in the flow under investigation by illuminating them with a pulsed laser light sheet which is orientated normal to the imaging axis of the camera (Fig. 1). The camera records the positions of the particles by stroboscopically illuminating the flow with at least two light pulses in short succession. By measuring the particle image displacement, either by particle tracking or locally applied statistical methods, the two-dimensional projection of the local velocity vector can be estimated using the magnification factor, *M*, and the laser pulse delay, $\Delta t = t - t'$.

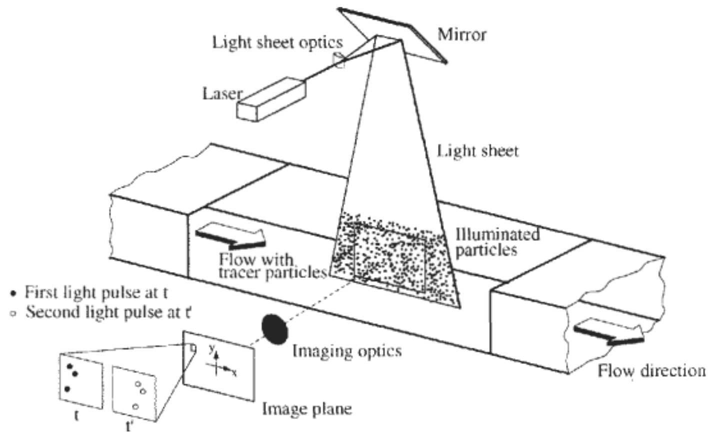

Fig. 1. Experimental setup for PIV recording in a wind tunnel.

In the past years, the PIV method has gained continual acceptance as a valuable fluid mechanics research tool in a wide variety of applications. In most cases, however, the method was employed in laboratory settings in which the setup and data acquisition times were secondary with respect to obtaining high quality data. The principal aim of DLR's efforts was to provide PIV systems for application in a wide variety of national and international wind tunnel facilities. This imposed a number of additional requirements not present in typical laboratory environments:

- the PIV system has to be easily portable,
- its components need to be modular to adapt it to each tunnel's unique features,
- reliability and the ability of remote control of all critical components of the PIV system are of principal concern due to the high cost of operating large wind tunnels such as the Deutsch-Niederländischer Windkanal

(DNW-LLF) with its 8×6 m^2 test section,
- the time between the actual PIV recording and the availability of the recovered PIV vector data sets has to be as short as possible (without reducing the quality of the data) in order to be able to rearrange the test program according to the results already obtained.

Based on the description of the measurement procedure as given above, DLR's PIV system will be described in the next sections.

2.2 Particles

PIV requires tracer particles to determine the flow velocity indirectly from the velocity of the tracer particles. In order to obtain a set of velocity data without gaps, a high and uniform seeding density in the region of interest is required. According to statistical simulations, at least 10 pairs of particles images per interrogation window are required to apply statistical evaluation methods. Such a seeding density, which is equivalent to ≈ 5 particles/mm^3, under practical conditions must also be achieved in regions where strong recirculation or velocity gradients are present.

For seeding the flow in the wind tunnel, a seeding system (Raffel et al., 1998a) consisting of one or more aerosol generators and a movable, remote-controlled seeding rake placed in the settling chamber is utilized.

The most common seeding particles for PIV investigation of gaseous flows are oil droplets which are generated by means of Laskin nozzles, see Echols and Young (1963). Each aerosol generator contains 40 Laskin nozzles and produces oil particles, the aerodynamic diameter of which is about 1 μm. The amount of particles can be controlled by switching four valves at the nozzle inlets. The particle concentration can be decreased by an additional air supply via the second air inlet.

As already mentioned for complete velocity vector fields a uniform seeding is required. Figure 2 shows a part of a PIV image of the investigation of the flow field behind a propeller as an example for seeding of a complex flow field with the above described devices. The seeding is very homogeneous in most of the PIV recording. However, an area with reduced seeding density due to the velocity lag of the tracer particles (an effect, which is integrated along the flow in the test section from the blade tip to the observation area) and due to the reduced air density inside the vortex core can be observed. This reduced seeding density, together with the strong velocity gradients inside the vortex core, lead to data drop out in this part of the observation area. It should be emphasized that this seeding situation, which in our opinion is close to optimal, can be achieved with some effort in most PIV experiments, even at the investigation of strong propeller, rotor or wing tip vortices.

Fig. 2. Typical PIV recording of a propeller tip vortex (20×20 cm^2).

2.3 Illumination

Mostly, pulsed Nd:YAG lasers with two independent oscillators are utilized as light sources for PIV applications in wind tunnels. The lasers are driven at repetition rates of 10 Hz, the pulse energy at $\lambda = 532$ nm is typically 2×320 mJ for a big (expensive) laser system and 2×150 mJ for a smaller laser system. The available maximum pulse energy is an important parameter of the PIV system as it finally determines (together with the sensitivity of recording sensor) the maximum size of the observation size, if the tracer particles with their optical properties and the illumination/recording setup are given. PIV measurements over long distances do not only require powerful lasers but also excellent characteristics of the spatial intensity distribution of the laser beam (hole-free without hot spots, especially in the midfield where it is most difficult to get), excellent co-linearity between the two beams of the two different oscillators, beam pointing stability (< 100 µrad) and energy stability (< 5%).

Compact and mobile pulse laser systems give a maximum pulse energy of 400 mJ per pulse at a wavelength of λ = 532 nm. Applications in large wind tunnels require higher pulse energies. The only solution (if laser amplifiers shall be avoided due to beam quality problems) is two combine two double oscillator systems. Such a laser system has been set up at DLR. It allows the following configurations:

- two separate double oscillator systems, 2 × (2 × 320 mJ); for two different experiments,
- two separate double oscillator systems, 2 × (2 × 320 mJ); for two different light sheet planes in the same experiment; light sheets can be either close together or overlapping or at two different areas of interest, (flow in front - undisturbed flow - and behind a model in the wind tunnel),
- two combined double oscillator laser systems, 2 × 600 mJ; large observation area; see Fig. 3, (Dieterle et al. 1998),
- two combined double oscillator laser systems, 4 × 300 mJ; 4 laser pulses, independently triggerable; 2 PIV recordings within a short time interval; for acceleration measurements and measurements of spatio-temporal correlation and spectra.

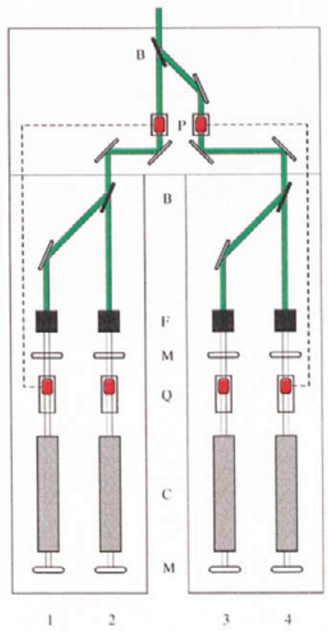

Fig. 3. Beam combination of four single-pulsed and frequency-doubled Nd:YAG lasers. (M) mirrors of the resonator, (C) cavity, (Q) Q-switch, (F) frequency doubler, (B) Brewster window, (P) Pockels cell.

2.4 Recording

For PIV recording video cameras incorporating progressive scan, full-frame interline CCD technology have become available recently which, contrary to the more common interline transfer CCD sensors, are capable of shuttering (exposing) and storing the entire array of pixels, not just every other line. Thus, these sensors immediately offer the full vertical resolution when the CCD is used in the shuttered mode. Such 'cross correlation cameras' allow the first illumination pulse to be placed at the end of the first (full) frame and the second illumination pulse to be placed at the beginning of the second (full) frame (Vogt et al., 1996). In practical illumination and recording situations, the minimum time delay between the two light pulses can be as low as 5 µs without cross talk between the two frames. This minimum time delay is small enough for most applications in aerodynamics (except supersonic flows).

Following this general approach, the present PIV camera systems additionally feature a non-standard, high resolution, digital video format consisting of 1008 by 1018 pixels and 1024 by 1280 pixels respectively. An enormous advantage of some of these cameras is that they are offered with both high resolution and sensor cooling which reduces the black current and increases the dynamic range to 12 bit. The gain in sensitivity is in the order of several f-numbers, allowing a much larger observation area with the same pulse laser. Using a 32^2 pixel interrogation window, the size of the CCD sensor translates to a spatial resolution of up to 32 by 40 discrete vectors. As the digital video signals of these cameras can not be viewed using a standard video monitor, a PC-interface card is necessary which transfers the digital data directly into the computer's memory (RAM) and thereby allows a continuous sequence of frames to be captured and viewed. A fiber optic transmission link allows for very long distances between camera and frame grabber. The focusing of the cameras is remotely controlled.

As video cameras are precisely triggered electronically (no delay due to mechanical shutters etc.), a further major advantage arises from the fact that several video cameras can be grouped in a very flexible and modular form and can be exposed by the same or different illumination pulses. The following arrangements are in use at DLR:

- two or more cameras, viewing perpendicular to the light sheet; same illumination; yields larger observation area,
- two or more cameras, viewing perpendicular to the light sheet; same illumination; different magnification at recording; yields overview and details of an unsteady structure in the flow simultaneously,
- two cameras in Scheimpflug arrangement, oblique viewing; same illumination; stereoscopic PIV,
- two cameras; two orthogonally polarized light pulses; slightly displaced light sheets; observation via polarizing beam splitter; dual plane PIV,
- four cameras in two Scheimpflug setups, two double oscillator lasers; two pairs of orthogonally polarized laser light pulses; viewing via polarizing beam splitter; two 3C-2D PIV recordings with very short time separation (acceleration, spatio-temporal correlation and spectra),
- four cameras in two Scheimpflug setups, two double oscillator lasers with slightly displaced light sheets; two pairs of orthogonally polarized laser light pulses; viewing via polarizing beam splitter; two simultaneous 3C-2D PIV recordings in two planes of the flow at the same time; full 3D vorticity vector.

The need to arrange the camera perpendicular to the light sheet poses problems in many industrial wind tunnel applications due to the limited optical access in the test section. During the development of stereoscopic PIV different arrangements (translation and angular method) have been studied. The result of different feasibility studies (Willert, 1997) and applications in different wind tunnels was that the angular method is best suited for a stereoscopic PIV system in aerodynamics. The angular method requires a Scheimpflug arrangement of the two cameras. It is obvious that, once the problem of evaluation of PIV recordings captured in non-symmetric Scheimpflug condition (oblique viewing) and with varying magnification on the recording has been solved, cameras can be placed at a wide range of angles between camera axis and light sheet, thus significantly reducing problems due to limited optical access in a test section.

As already mentioned, in an industrial wind tunnel it is not possible to operate the PIV system manually due to long distances between control room and the PIV system and due to the limited time available for the test. After system installation and adjustment, most parts of DLR's PIV system (the laser system beside the test section, the seeding rake in the settling chamber and the objectives and cameras within the test section) can be operated via remote control. The laser system and the cameras are triggered and synchronized by a so-called 'sequencer,' consisting of a 10 Hz trigger source and a programmable, PC-controlled, delay generator. If the cables for image data transfer between the cameras and their acquisition PCs are limited in length, the PCs must be placed close to the test section and equipped with keyboard extensions. The operator can check on-line the quality of the digital particle images and if necessary focus the objectives and change the position of the seeding rake in the settling chamber.

2.5 Evaluation

The availability of 'cross correlation' cameras for PIV applications in aerodynamics consequently leads to the use of cross correlation techniques for the evaluation of the PIV recordings. Two "power of two" sized rectangular interrogation windows of the first and the second frame are correlated via Fast Fourier Transform (FFT) algorithms and the location of the correlation is determined with sub pixel resolution by means of the three-point peak fit estimator.

An FFT-based cross correlation algorithm using completely free-shaped and free-sized interrogation windows has been developed by Ronneberger et al. (1998). These cross correlation algorithms employ two interrogation windows of different size. Only the size in *x*- and *y*-direction of the smaller interrogation window must be set prior to the evaluation. The size of the larger interrogation window is determined in a way that it will contain the matching particle images even in that area of the PIV recording with highest flow velocity. This has only to be done once. No longer multi-pass evaluation is required to adapt the step width between the interrogation windows in order to achieve optimal evaluation.

It is now also possible to define interrogation windows of non-rectangular shape. The first important advantage is that one can adapt the size of the interrogation window to the fluid dynamics of the experiment. In regions with strong velocity gradients in one direction, e.g. a boundary layer which has big gradients normal to the wall, it can be useful to decrease the window size perpendicular to the wall while increasing it parallel to the wall. In PIV recordings containing objects (an airfoil for instance), one may now perform a local adaptation of the interrogation window shape, so that one is able to measure the boundary layer very close to the curved wall (see Figs. 4 - 6).

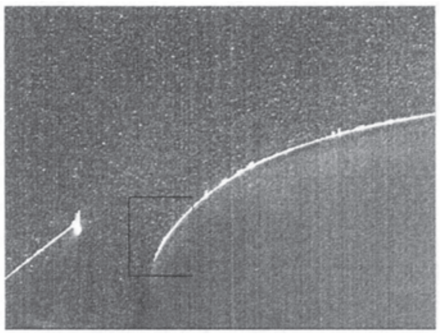

Fig. 4. PIV recording with curved walls and reflections in the vicinity of an airfoil with slat and gap.

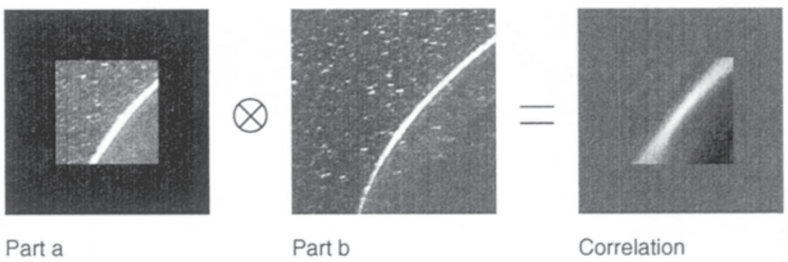

Fig. 5. With a rectangular interrogation window it is not possible to resove the flow very close to the airfoil.

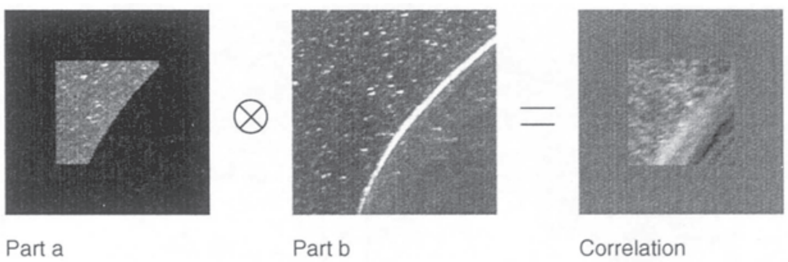

Fig. 6. With a free shaped interrogation window the flow close to the profile can be resolved. A peak is clearly visible in the correlation plane near to its center.

2.6 Post Processing

Absolutely required for PIV application in industrial wind tunnels is a software, which displays samples of the recorded video images, allows to assess their quality with respect to PIV (seeding density, brightness of particle images, displacement of particle images, value of correlation coefficient, number of outliers, areas of interest – vortices for instance), and presents the vector plots of the instantaneous flow field (raw data) quasi on line for further planning of the test. This software must be fast and simple.

Further analysis of the vector plots, such as image de-warping, data validation (i.e. removal of outliers), overlay of model contour, vorticity, divergence etc., can be performed on a further workstation connected to the image acquisition system via network in order not to interrupt the image acquisition in the wind tunnel.

Advanced analysis (details of the flow field, structures, statistical data, 3D or 4D presentation of data sets and animation for better visual perception, comparison with results of numerical calculations) will usually be performed on powerful graphical workstations. Today, mostly commercial software packages can be utilized for advanced analysis of PIV vector maps, the same as will be utilized for the analysis of numerical data. However, it has to be kept in mind that PIV data – as all experimental data – contain noise and – up to now – have been determined on a regular, rectangular grid in contrast to numerical data, which – very often - are available on an unstructured grid. Thus, for high quality comparison of experimental PIV and numerical data some preprocessing of the PIV data must be carried out.

3. Application of PIV in Aerodynamics

During the past decade more than 30 different applications have been performed with DLR's mobile PIV system, which has continually evolved during this time from a low power laser - photographic recording to a multi-laser - multi-camera system. Low speed boundary layers (Kähler et al., 1998) have been investigated as well as transonic flows at Ma = 1.27 with shocks embedded in the flow field (Raffel and Kost, 1998). In the following section a few examples of these applications shall be given.

3.1 Flow Field on Delta Wing

A joint research project of three German Collaborative Research Centers (SFB 253, 255 and 259) and the German Aerospace Center deals with the investigation of a large model of the hypersonic research configuration ELAC-1 (Elliptical Aerodynamic Configuration). ELAC-1 represents a space transporter for horizontal take off and landing. It is a delta wing with an elliptical cross-section, rounded leading edges and integrated winglets in the afterbody. Different experiments have been performed with the ELAC configuration (force, momentum, pressure distribution, boundary layer measurements). The results of the PIV measurements have been described in detail by Dieterle and Peiter (1998) and Neuwerth et al. (1998).

The experiments were carried out in the DNW-LLF's closed test section of 8×6 m^2. The model of the delta wing configuration ELAC-1, adapted in scale to this particular surrounding, has a total length of l = 6 m; its sweepback angle of the leading edge is 75° and, consequently, the full span 3.2 m. The model is supported by a rear sting. The PIV measurements had to be carried out in the cross section x/l = 0.6 on the port side of the delta wing. The area of interest was expected to be about 0.3 m^2 in size. Due to the high running costs of the wind tunnel facility, the PIV measurements – excluding system installation – were limited to the period of about one working day. During this time 15 different flow conditions had to be investigated. The main flow velocity v was equal to 15, 20, 30, 50 and 70 m/s and the angle of attack α to 12°, 18° and 21°.

The objectives of the flow field investigation were to illuminate the object plane with sufficiently high intensity and to resolve an observation area of about 0.3 m^2 in order to investigate flow structures down to a few centimeters in size. A feasible solution was (i) to combine four single-pulsed laser oscillators in which two of them fire simultaneously, generating light pulses of sufficiently high energy and (ii) to employ two identical CCD cameras, which simultaneously take pictures of neighboring regions of the flow field, capturing a total area of the size required but without a considerable loss in resolution.

The experimental setup can be seen in Fig. 7. The cameras were arranged in pilot's view on the port side of the delta wing at a working distance of about 4 m and directly mounted on the model sting. Their position relative to the model was fixed and they did not need to be rearranged when changing the angle of attack. The laser system was placed beside the closed test section. A combination of spherical and cylindrical lenses formed the laser beam into a light sheet, which entered the test section through a small opening in the wall. The light sheet illuminated the cross section $x/l = 0.6$ of the model. In order to be able to observe the flow region close to the rounded leading edge of the delta wing from the cameras' position, their image planes as well as the light sheet were not perpendicular to the surface of the model but slightly tilted by an angle of 7°. The light sheet optics had to be readjusted when changing the angle of attack.

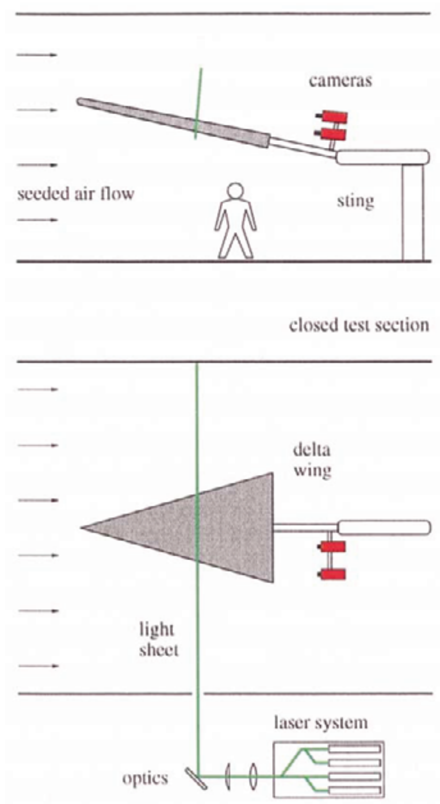

Fig. 7. Schematic view of the experimental setup in the 8×6 m^2 test section of DNW-LLF.

Two identical CCD cameras with full-frame interline transfer sensors take single-exposed double images of the tracer particles at an interval Δt of a few microseconds each.

The cameras took 2×40 image pairs per run resulting in 168 Mbytes image data per run, 838 Mbytes per session or more than 2.5 Gbytes for the whole campaign, mainly limited by the computer memory and mass storage available at the time of the measurement.

As an example, the combined field of instantaneous velocity on the leeward side of the delta wing at $v = 50$ m/s, corresponding to $Re \approx 2 \cdot 10^7$, and $\alpha = 21°$ is shown in Fig.8. The inboard camera captured an observation area of 400×400 mm^2, the outboard camera an additional area of about 270×230 mm^2. So the outboard camera's field of view was not fully used for the measurements. A total flow field of 0.22 m^2 size has been investigated with the digital PIV system. The individual vectors in Fig. 8 represent the local mean flow velocity within an area of 12.5×12.5 mm^2 in the object plane. Their length corresponds with the magnitude of velocity.

The vector plot shows on the left – in the outboard camera's field of view – a shear layer apparently separating from the rounded leading edge of the delta wing. Small vortices are arranged on the shear layer, each of them clockwise rotating. The shear layer rolls up to the big primary vortex, clockwise rotating as well, which covers almost completely the inboard camera's field of view. Obviously, the flow on the leeward side of the delta wing separates a second time creating a small counterrotating secondary vortex close to the model's surface, centered at $y = -0.75$ and $z = 0.16$. The maximum velocity $v_{max} \approx 90$ m/s occurs below the center of the primary vortex.

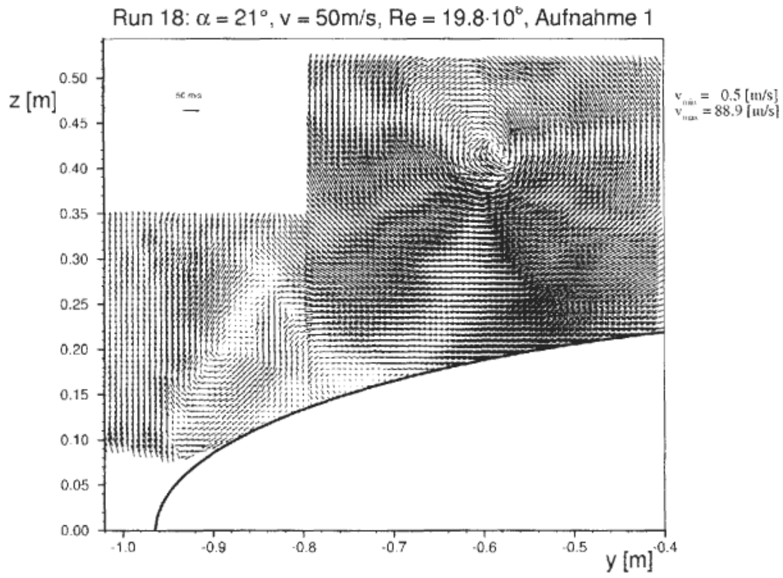

Fig. 8. Instantaneous velocity field on the leeward side of the delta wing configuration ELAC-1 derived from the pictures of two CCD cameras placed in pilot's view on the port side of the model as shown in Fig. 7.

3.2 Propeller Slipstream Investigation

Investigation of the instantaneous flow field of pitching or rotating models is the most demanding and most adequate task for particle image velocimetry. At present no other velocity measuring technique is able to give such results. PIV enables to obtain complete velocity field data even in case of large cycle-to-cycle variations. The fact, that the measuring time necessary for the application of PIV is small (≈ 10 µs) compared to the time required for one revolution cycle (≈ 7000 µs corresponding to 1/rpm × 60), makes PIV a useful tool for the investigation of flow fields of rotor or propeller systems. In addition to the problems discussed so far, image capture has to be performed with respect to the angular position of the rotor or propeller. In the simplest case, this can be done by just measuring the angular position of the model or – if measurements at a given angle are required – by providing sophisticated triggering systems in order to keep the laser repetition rate constant and ensure phase locked recording. The modular approach of DLR's PIV system allows such features by extending the functionality of the sequencer and its software. The capabilities of the system, when applied to large scale model rotor testing in the open test section of DNW-LLF, have been reported by Raffel et al. (1998b).

In this section some results of the investigation of the unsteady flow field downstream of a modern high speed propeller shall be presented (De Gregorio et al., 1998). These investigations have been carried out within a research project called APIAN (Advanced Propulsion Integration Aerodynamics and Noise) which has been launched under the coordination of Aerospatiale in the 4th framework program of the Brite-EuRam projects. The main objective of the APIAN project is to investigate the aerodynamics and the acoustic behavior of new high speed propellers, as well as the propeller and airframe integration using numerical and experimental methods. The PIV technique has been utilized within the APIAN project in order to investigate the highly unsteady flow phenomena in the propeller slipstream, to save costs by reducing wind tunnel operation time, and to compare the experimental PIV results with those of numerical calculations. The tests have been performed in the DNW-LST facility: a continuous atmospheric wind tunnel with closed walls, a test section 3 m wide and 2.25 m high, a maximum air velocity of 80 m/s, and a Mach number range between 0 and 0.23. It is driven by a fan of 700 kW. The PIV measurements have been carried out downstream of an isolated propeller test rig. The propeller model, including an internal six component rotating balance, has been mounted on the external balance of the tunnel as shown in Fig.9 . The model represents a new type of high speed propeller (Mach 0.7-0.8) which is composed of six blades and has a diameter of 500 mm. All tests have been performed at the same wind tunnel velocity (80 m/s), with the same blade angle of 40.4 degree but with different propeller rotational speed (8000 and 8650 rpm, in order to investigate the influence of the rate of advance coefficient J on the slipstream) and for different incidence and jaw angle (0°, +10°, –10°) of the propeller. The reference system is related to the model in order that it does not change when the model position is varied with respect to the wind tunnel. The system is defined as follows: the plane $z = 0$ is a horizontal plane containing the axis of rotation, the plane $y = 0$ is a vertical plane containing the

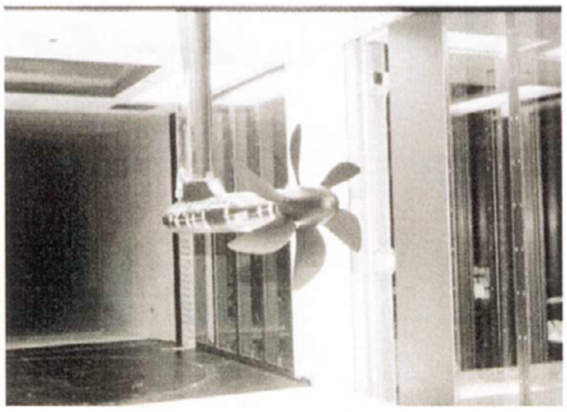

Fig. 9. The isolated test rig with the APIAN propeller in DNW-LST wind tunnel.

axis of rotation, and the plane $x = 0$ is a vertical plane containing the trailing edge of the blade tip profile.

To correlate the propeller blade position to the acquired vector field a custom made Propeller Angle Measurement (PAM) device has been designed and built. A reset signal per each propeller revolution and the Q-switch signal from the laser are used by the PAM system to evaluate the propeller position. This information is transferred to the acquisition PC, that stores the angle information in the image file. The complete acquisition system has been driven from the control room by a PC.

As an example of the results achieved in the APIAN investigations, the instantaneous flow field for zero degree of incidence and jaw angle, measured in the area from 155 mm to 350 mm along the x direction and from 97 mm to 292 mm along the y direction, is presented in Fig. 10. The mean component of the velocity has been subtracted in order to enhance the visibility of the vortical structures. This figure clearly presents two sequential blade tip vortices cut by the light sheet plane. Furthermore, the shear layer in the wake of one of the blades is present (in Fig. 10 it is marked by 'A').

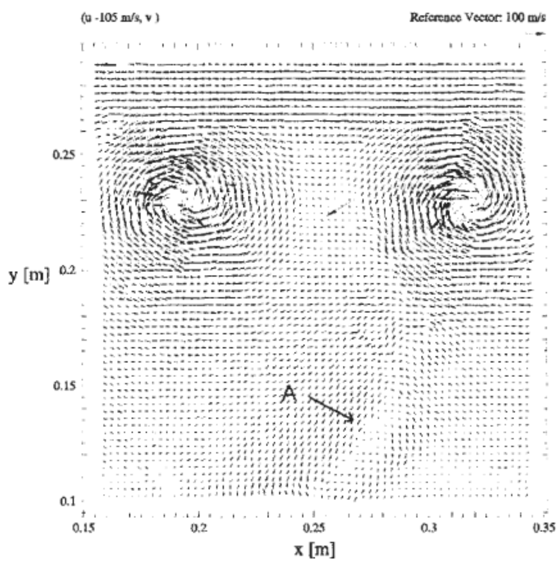

Fig. 10. Instantaneous velocity field for zero degree of incidence and jaw angle.

3.3 Rotorcraft Model Investigations

With increasing use of civil helicopters the problem of noise emission of helicopters became more and more important. Many research projects on rotorcraft noise have shown that blade vortex interaction (BVI) is a major source of impulsive noise. As BVI-noise is generated by the induced velocities of tip vortices, it depends on vortex strength and miss-distance, which itself depends on vortex location and orientation and convection speed relative to the path of the advancing blade. The detailed study of these vortices is of particular interest for progress towards quieter rotorcraft. With standard PIV the velocity components of the vortex in the plane, as cut by the light sheet, are obtained in the form of a 2C-2D instantaneous velocity field. However, for complete understanding of the fluid mechanical phenomena as well as input to numerical simulations, exact information about the axial velocity component within the core of the tip vortex and its orientation in space (true diameter of vortex core) are required. This information can only be achieved by a 3C-2D stereoscopic PIV system.

To adapt the stereoscopic approach at PIV as developed in laboratory to an industrial wind tunnel environment, a number of additional developments are necessary. First of all the optical access in wind tunnels rarely permits the imaging configuration to be symmetric as it is usually implemented for stereoscopic PIV. The Scheimpflug setup had to be adapted to non-symmetric arrangement of the cameras. Another requirement is that the small seeding particles have to be imaged over large distances exceeding 9 meters. This makes the use of large focal length lenses with large light collecting capability (i.e. small f-numbers) necessary. As the measurement precision of the out-of-plane velocity component increases as the opening angle between the two cameras reaches 90 degrees, it is not always possible to mount the camera on a common base, much less to provide a symmetric arrangement. During investigations of helicopter rotors there is no access to the wind tunnel's test section: remote control of all elements of the focusing device and the Scheimpflug adapter of the camera is essential.

A first test with a non-symmetric PIV imaging system of DLR's mobile PIV System has been performed in the open test section of DNW-LLF on a rotorcraft model. The measurements were designed to investigate the unsteady flow field of the rotorcraft model blade tip vortex.

The measurement equipment was arranged as shown in Fig. 11. The laser (2×320 mJ) was set up on the floor of the test section. The two recording cameras were located at the side of the nozzle of the open test section, and were placed in a vertical plane intersecting the observation area. The angle between the camera axes and the normal of the observation area was approximately 12°. Two sensitive and high spatial resolution CCD cameras have been used to image an area of 25×30 cm^2 over 9.5 m from each camera.

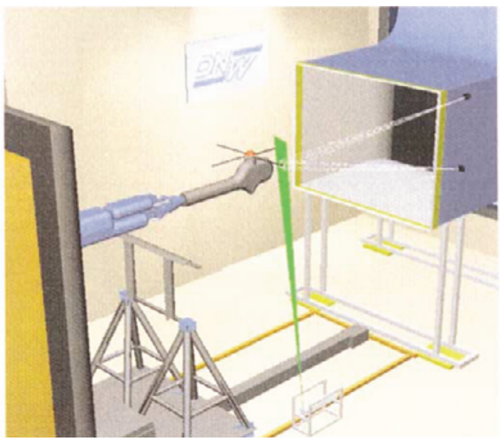

Fig. 11. Experimental arrangement of the stereoscopic PIV system for the investigation of a helicopter rotor flow field in the open test section of DNW-LLF.

Figure 12 shows an example of a flow velocity field as obtained during this test. The vector field has been rotated 90° clockwise with respect to the camera's view as shown in Fig. 11. The rotor blade tip, which had just passed the observation area (light sheet plane) when the recording was taken, had given rise to the vortex present in Fig.12 (upper part). The lower part of Fig. 12 presents the transverse and normal component of the velocity along a line indicated in the vector plot (upper part of Fig. 12). By application of stereoscopic PIV it is now possible to obtain the third, out-of-plane velocity component as well. Especially the axial velocity component shows strong spatial gradients.

This axial velocity component is of special interest for the understanding of vortices, for rotor tip vortices as well as for wake vortices behind airplanes in landing or starting configuration. If, as it is mostly the case, these vortices exhibit an unsteady behavior, the only possibility to measure the velocity field conclusively with all three components is by application of stereoscopic PIV.

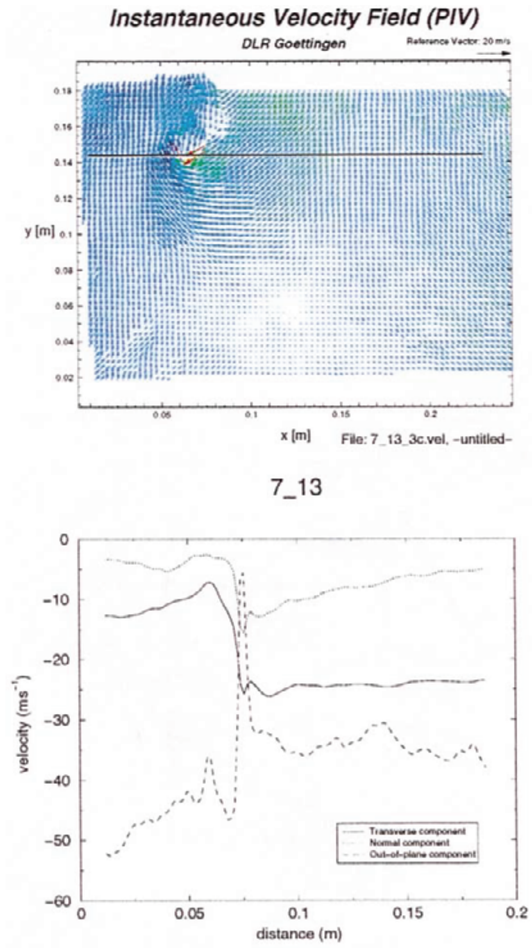

Fig. 12. Instantaneous velocity vector field of rotor tip vortex (upper part) and in-plane and axial velocity components (lower part) along line, as indicated in upper part.

3.4 Boundary Layer Investigations

Particle image velocimetry has been widely used to reveal the instantaneous spatial structures in boundary layers. By means of stereoscopic PIV it is possible to determine the double correlation tensor of fluctuating velocities in order to deduce the average dimensions of the dominant flow structures (Kähler et al., 1998). Though the out-of-plane velocity component can be measured by means of stereoscopic PIV, there is still not all information available to describe all flow properties. Therefore, new approaches with multi-pulse multi-camera PIV systems have been developed at DLR. Figure 13 shows a setup with two different light sheets, slightly displaced, and four different cameras. By means of two pairs of orthogonally polarized laser light pulses, a pair of polarizing beam splitter cubes and two CCD camera pairs in stereoscopic configuration, it is possible to determine the acceleration of moving flow structures, and (in the configuration presented in Fig. 13) the distribution of the 3D vorticity vector. Figure 14 presents a result of a first application of this setup in a boundary layer, which was excited by an acoustic distortion in order to investigate instabilities and transition. Both vector maps (flow direction from right to left) have been recorded at the same time, however, at different positions in the boundary layer. It can be clearly seen that the same structure (Λ-vortex) as visible in the upper vector field (closer to the wall) extends in height (lower vector field, light sheet slightly overlapping with the first one, but farther away from the wall). Major progress at the investigation of unsteady structures is expected by the different possibilities offered by multi-pulse multi-camera setups (see sec. 2-4.).

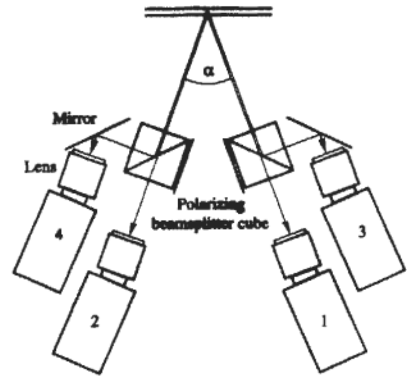

Fig. 13. Experimental setup for multi plane stereoscopic PIV.

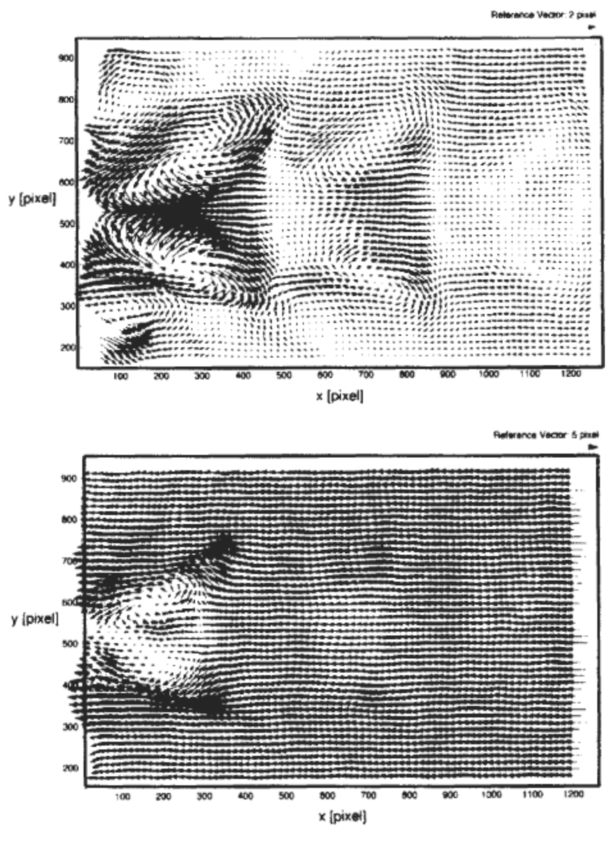

Fig. 14. Instantaneous velocity vector field with Λ-vortices recorded simultaneously in two planes parallel to the wall but at different height (upper field closer to wall). Flow from right to left.

4. Conclusions

DLR has developed a mobile PIV system for applications in large industrial test facilities (low speed and transonic flows) for recording of two velocity components of the instantaneous flow velocity field in a plane of the flow (standard PIV). This standard PIV system has been successfully employed for more than 30 different investigations. Standard PIV (2C-2D) is now a mature tool for application in large industrial wind tunnels. Extension of this system to multi-pulse multi-camera configurations is under way. Especially stereoscopic PIV (3C-2D) is under development (successfully at laboratory scale) and can be brought into operation in large wind tunnels within the next two years.

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Author Profile

Jürgen Kompenhans: He received his doctor´s degree in physics from the University of Göttingen in 1976. Since 1977 he is working for DLR as scientist. Starting with experimental work on problems of aeroacoustics he is now developing and applying non-intrusive optical measuring techniques for aerodynamic research in wind tunnels (mainly Particle Image Velocimetry). Since 1985 the PIV-group, guided by J. Kompenhans, has developed a mobile PIV system, which can be operated under the rough environmental conditions of a large wind tunnel. This system has been successfully applied in different flow facilities as well to low speed as to high speed flows. He is co-ordinator and task manager of different European projects in aerodynamics utilizing the PIV technique.

Markus Raffel: He received his degree in mechanical engineering in 1990 from the Technical University of Karlsruhe and his doctorate in 1993 from the University of Hannover, Germany. He started working on particle image velocimetry at DLR Göttingen in 1991 with emphasis on the development of PIV recording techniques in high-speed flows. In this process he applied the method to a number of aerodynamic problems mainly in the context of rotorcraft investigations.

Lutz Dieterle: He studied mineral processing at the Technical University of Clausthal-Zellerfeld, Germany, and made his Diploma in mining December 1992. He worked first as a DECHEMA-scholar and afterwards as a scientific employee at the *Institut für Mechanische Verfahrenstechnik und Umweltverfahrenstechnik* of the TU Clausthal. November 1996 he got his Ph.D in mechanical process engineering with a thesis on the development of a particle image velocimetry (PIV) system for microscopic turbulent flows. Since March 1997 he has worked at the *Institut für Strömungsmechanik* of the DLR (*Deutsches Zentrum für Luft- und Raumfahrt*; German Aerospace Center) in Göttingen, Germany. He is responsible for the planning and implementation of PIV measurements in industrial wind tunnels.

Tim Dewhirst: He gained his B.Sc. in Physics from Edinburgh University in1994 and his Ph.D in Physics in 1998, also from Edinburgh University. He has been working in the field of Particle Image Velocimetry for the past eight years, and during this time worked also for German Aerospace Center as part of the Institute of Fluid Mechanics. His main interests lie in applications of Fourier optics, image processing techniques and digital imaging technologies.

A. F. Heinrich Vollmers: He received his Diploma in 1972 from Ernst-Albrecht-University in Kiel working on particle detectors for a space probe. Since then he has worked with German Aerospace Center in Göttingen in several fields: turbulence modeling, data visualization, data analysis, particle image velocimetry.

Klaus Ehrenfried: He studied physics at the University of Göttingen, Germany. Diploma in physics February 1988. Ph.D. thesis at the University of Göttingen, Germany. Ph.D degree in physics June 1991. Title of the Ph.D thesis: Numerical investigation of vortex-airfoil interactions in transonic flows. From 1991 to 1993 researcher at the Max-Planck-*Institut für Strömungsforschung* in Göttingen. Worked in the field of numerical simulations of transonic flows with vortices. From 1993 to 1998 researcher at the *Institut für Strömungsmechanik* of the DLR (*Deutsches Zentrum für Luft- und Raumfahrt*; German Aerospace Center). Numerical and experimental work in the field of sound generation in flows with vortices. Since 1998 scientific assistant at the Technical University of Berlin, Germany. Teaching and research in the field of aeroacoustics.

Christian Willert: He received his BS degree in Applied Science from the University of California at San Diego (UCSD) in 1987. Subsequent graduate work in experimental fluid mechanics at UCSD lead to the development of several nonintrusive measurement techniques for application in water (particle tracing, 3-D particle tracking, digital PIV). After receiving his Ph.D in Engineering Sciences in 1992, he assumed post-doctoral positions first at the Institute for Nonlinear Science (INLS) at UCSD, then at the Graduate Aeronautical Laboratories at the California Institute of Technology (Caltech). In April 1994 he joined DLR Göttingen's measurement sciences group as part of an exchange program between Caltech and DLR (i.e. Center for Quantitative Visualization, CQV). There he continued to work in the development and application of PIV techniques with special emphasis on wind tunnel applications. Since 1997 he is developing and applying Doppler global velocimetry at DLR Cologne.

Kurt Pengel received his degree in meteorology in 1982 from the University of Hannover, Germany. He started working at the German-Dutch Windtunnel in 1986. There, he is responsible for the implementation of new measuring techniques. His PIV concerns began in 1995. Since that time he applied PIV in a number of wind tunnel projects and published his experiences in several papers.

Christian Joachim Kähler: He received his Diploma degree in Physics in 1997 from the Technical University of Clausthal and he is now registered at the Georg-August-University Göttingen working on turbulence research. In addition he is employed at the German Aerospace Center working on the development of PIV based techniques for fundamental flow investigations.

Andreas Schröder: He studied physics at the University of Göttingen, Germany. Diploma in physics May 1996. Title of Diploma: *Untersuchung der Strukturen des laminaren Zylindernachlaufs mit Hilfe der Particle Image Velocimetry* (*PIV*) *Meßtechnik* (Investigations of the structures in the laminar wake behind a cylinder utilizing PIV). Since 1996 researcher at the *Institut für Strömungsmechanik* of the DLR (German Aerospace Center) in Göttingen. Experimental work in the field of transition of boundary layers by means of stereoscopic PIV.

Olaf Ronneberger: He received his diploma in physics in 1998 from the Institute of nonlinear Dynamics, University of Göttingen. Before and during his study he worked as programmer and scientist in the PIV-group around Dr. Kompenhans in the DLR. Since the first successful application of Dual-Plane PIV together with Dr. Raffel during an exchange at the California Institute for Technologies 1994 his research interest were the improvement of the PIV technique. In 1998 he started his thesis at the Institute for Computer Science, Chair of Pattern Recognition and Image Processing, University of Freiburg. In a collaboration with the German Weather Service and the Swiss Meteorological Institute he works on automated recognition of 3D volume images from airborne pollen grains (http://come.to/pollen_recognition). His research interests include 2D/3D image processing, grey scale invariants and pattern recognition.