APPLICATION OF PARTICLE IMAGE VELOCIMETRY FOR THE INVESTIGATION OF HIGH SPEED FLOW FIELDS

J. Kompenhans*  A. Gilliot
A. Arnott  J.-C. Monnier
A. Agocs
German Aerospace Center (DLR)  Office National d'Etudes et de Recherches
Institute of Aerodynamics and Flow Technology  Aérospatiales (ONERA)
Bunsenstrasse 10  Institut de Mécanique des Fluides de Lille
37130 Göttingen, Germany  5, Bd. Paul Painlevé, 59045 Lille, France
Email: juergen.kompenhans@dlr.de  Email: gilliot@imf-lille.fr

Abstract. For the past few years particle image velocimetry (PIV) has been increasingly used for aerodynamic research and development. This is mainly due to the unique feature of the PIV technique, which allows the recording of a complete velocity field in a plane of the flow within a few microseconds. Thus, PIV 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 the PIV teams of DLR and ONERA to develop reliable, modular PIV systems for use in low speed wind tunnels. The application of PIV in high-speed flows poses a few more problems, mainly due to limited optical access in the test facilities. Technical progress made in the last years allowed the PIV teams of DLR and ONERA to develop reliable, modular PIV systems for use in low speed wind tunnels. The application of PIV in high-speed flows poses a few more problems, mainly due to limited optical access in the test facilities. This paper will briefly summarize the state-of-the-art of PIV by describing the basic features of a PIV system and will present some results of recent PIV applications within industrial projects in low speed flows. An application of PIV in ONERA’s S2 wind tunnel, which has jointly been performed by ONERA and DLR, will be utilized to illustrate the state-of-the art of PIV in transonic flows.

Key words: particle image velocimetry, transonic flows, seeding, velocity lag, shocks, OAT15 wing, S2 wind tunnel.

1 INTRODUCTION

Over the past decade particle image velocimetry (PIV) has matured from its developmental stage to a reliable whole field 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 simulators, 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 in 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 in regard to obtaining the information about the unsteady flow field.

The description of the problems as given above leads to the definition of requirements, which should be fulfilled when PIV is applied in aerodynamics.

First of all a high spatial resolution of the data field is necessary for resolving large as well as small scale structures in the flow. This condition directly influences the choice of the recording medium (large format CCD sensor for digital imaging). An equally important second condition is the requirement for a sufficiently high density of the experimental data to allow a meaningful comparison with numerical results. Thus, the image density, that is, the number of detectable particle images per given area in the recording, must be as high as possible. As the flow velocity is indirectly measured by means of the measurement of the velocity of tracer particles added to the flow, powerful seeding generators along with uniform particle dispersion systems are necessary. It is obvious that the particles themselves need to follow the flow faithfully, which - in airflows - requires the use of very small tracer particles, typically in the 1 µm range. These particles scatter very little light which imposes a third requirement to the successful application of PIV in aerodynamics: A powerful pulsed laser with at least two pulses per cycle is essential for the illumination of the small particles within the flow field.

2 EXPERIMENTAL SETUP FOR PARTICLE IMAGE VELOCIMETRY FOR APPLICATION IN WIND TUNNELS

2.1 General

Adrian¹ and Hinsch² give detailed descriptions of various implementations of the PIV method, which have been developed during the past 15 years. Recently an overview about PIV systems (standard, stereoscopic, holographic PIV) and their
application in different areas has been presented in 19 papers published in a special issue of Measurement, Science and Technology. PIV systems as utilized for flow field investigations in wind tunnels have been described by Willert et al. Especially the practical aspects appearing at the application of PIV in industrial environments have been addressed in detail in the practical PIV guide prepared by Raffel et al. In order to be able to compare different PIV systems, these systems should be classified according to what kind of information they can extract from the flow field. Standard PIV as it has been developed in the beginning of the '80s measures only two components of the velocity vector in a plane of the flow. Holographic PIV will allow measuring all three velocity components in a volume of the flow. Following the classification as given by Stanislas and Royer, one can distinguish between:

- 2C-2D PIV (2 components of the velocity vector in a plane; standard PIV),
- 3C-2D PIV (3 components of the velocity vector in a plane; stereoscopic PIV; dual plane PIV),
- 2C-2.5D PIV (standard PIV; scanning different light sheets in temporal sequence),
- 2 x 2C-2D PIV (standard PIV in several (two or a few) planes, however, simultaneously),
- 3C-3D PIV (3 components of the velocity vector in a volume; holographic PIV).

Of course complexity of a PIV system will increase towards full 3C-3D capability. Also, the stage of development is quite different: 2C-2D standard PIV is now a mature technique, whereas holographic PIV still requires considerable scientific and technological effort.

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 oriented normal to the imaging axis of the camera (Figure 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, \( \Delta t = t - t' \).
2.2 PIV system for application in wind tunnels

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. A different philosophy towards the application of PIV was taken at the European aeronautical research establishments such as DLR and ONERA. The principal aim in these 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 larger wind tunnels such as the Deutsch-Niederländischer Windkanal (DNW-LLF) with its 8 x 6 m² 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 due to the results already obtained.

Based on the description of the measurement procedure as given above five sub systems can typically be distinguished in a PIV setup:

- particles,
- illumination,
- recording,
- evaluation,
- post processing.

A more detailed description of the different sub systems is given by Kompenhans et al. 7

<table>
<thead>
<tr>
<th>PIV system for wind tunnels</th>
<th>Wind tunnels</th>
<th>Applications</th>
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<tbody>
<tr>
<td>Area</td>
<td>DNW-LLF</td>
<td>Wake vortex</td>
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<td></td>
<td>ONERA-F1</td>
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<td></td>
<td>ONERA-catapult tunnel</td>
<td>Engine integration</td>
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<tr>
<td>No. of data points per camera</td>
<td>DNW-LST</td>
<td>Propeller</td>
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<tr>
<td>60 x 75</td>
<td>DNW-NWB</td>
<td>High lift configuration</td>
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<td>with 50% overlap (4-fold over-sampling)</td>
<td>AIRBUS-D L SWT</td>
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<tr>
<td>No. of cameras</td>
<td>2 ... 4</td>
<td>Transonic flow</td>
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<tr>
<td>1 ... 10</td>
<td></td>
<td>Compressor cascade</td>
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<td>Pulse separation</td>
<td>~ 10 µs</td>
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<td>Time for evaluation</td>
<td>&lt; 10 s</td>
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<tr>
<td>of recording</td>
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<tr>
<td>Frame rate</td>
<td>3 ... 15/s</td>
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Table 1: Present status of mobile PIV systems of DLR and ONERA and examples of their recent applications in large industrial test facilities.
Table 1 lists the main features of DLR's and ONERA's mobile PIV systems in their present configurations together with the major applications and wind tunnels where they have been utilized. Standard PIV (2C-2D) is now a mature tool for application in large industrial wind tunnels. Extension of these systems to multi-pulse multi-camera configurations is under way and has already led to considerable new insight into the structure of turbulent boundary layers\(^8\). Especially stereoscopic PIV (3C-2D) has undertaken a very successful development and adaptation for use in large-scale wind tunnels\(^9\) in the last two years. Stereoscopic PIV will be brought into routine operation even in large wind tunnels within the next years after some technical improvements such as fast and reliable calibration procedure, remote control of camera position and focusing have been performed.

3 APPLICATION OF PIV IN LOW SPEED FLOWS

During the past decade more than 40 different applications have been performed with the mobile PIV systems of DLR and ONERA, which have continually evolved during this time from low power laser-photographic recording to multi-laser-multi-camera systems. In the following section a few examples of such applications in low speed flows shall be given.

3.1 High lift configurations

In the EUROPIV project\(^9\) a full-scale test in an industrial wind tunnel employing PIV was performed. The aim of this task was to demonstrate the possibility of useful PIV measurements in an industrial environment and with industrial constraints. A three-day test campaign was performed in the AIRBUS-D LSWT low speed wind tunnel in Bremen. The model was a two-dimensional high lift wing profile (ONERA RA 16SC1) with a leading edge slat. It was set at high angle of attack (16° to 21°). The objective of the investigation was to study the flow in the slat passage and on the suction surface of the wing, in the region of interaction of the slat wake with the main body’s boundary layer. The model (50 cm in chord and 2 m in span) was designed and manufactured by ONERA, the PIV measurements were performed by DLR.

![Figure 2: Comparison between the mean velocity map (a) obtained by averaging 100 PIV instantaneous maps and one (b) of these instantaneous velocity maps. The flow is observed in the gap between the slat and the main body.](image-url)
Figure 2 presents a mean velocity map obtained by averaging 100 PIV recordings in the gap between the slat and the main body and for comparison one single instantaneous flow velocity field. A large recirculation region is clearly visible and measured in considerable detail. The difference between instantaneous and averaged velocity fields becomes quite obvious (center and size of vortex, shear layer etc.).

In parallel to these experiments, Dassault Aviation developed numerical simulations of the same flow. Unsteady two-dimensional Navier-Stokes computations were performed as well as steady predictions based on turbulence models. Comparisons have been performed so far, mainly on the mean properties of the flow. As an example, Figure 3 presents a comparison of the mean streamlines in the passage between the slat and the main body. This comparison shows that the predictions based upon turbulence models are quite good. This is not true in the region of interaction of the slat’s wake with the main body’s boundary layer. This discrepancy was expected and was the main reason for choosing this flow configuration. It is mainly due to a weakness of the Reynolds average models. In fact, PIV vorticity maps show a very strong vortex shedding in the slat’s wake and a mixing with the body’s boundary layer, which is much faster than given by the predictions. The unsteady computations performed by Dassault show vorticity levels comparable to the experiment but with different spatial distribution, due to the mesh size which is too large.

### 3.2 Engine integration

PIV is a well-suited technique to study complex three-dimensional unsteady flows such as for the investigation of interference problems at engine integration with interactions between flow, jet and structure. In co-operation between NLR and DLR some tests have been performed in DNW-LST.

As an example of the results which can be obtained in such tests Figure 4 presents the flow field for $\alpha = 6^\circ$, and $\omega = 13300$ rpm in a combination of three instantaneous flow fields, which have been captured independently in time, and the time-averaged
The magnitude of the velocity in the measurement plane and the vorticity component normal to this plane is color-coded. The expanding jet behind the CRUF simulator and the shear layer can be clearly seen. The velocity gradient normal to the main flow direction decreases in the shear layer with increasing width of the jet. This results in a decrease of the vorticity along the shear layer. The vorticity field indicates the generation of a second shear layer below the engine as well as the wake of the wing.

### 3.3 Conclusions for application of PIV in low speed flows

As the state-of-the-art of PIV application in low speed wind tunnels differs from that in high-speed wind tunnels, at this point some conclusions for low speed flows shall be made:
- Considerable progress has been made with the PIV technique in the past 10 years due to technological progress.
- Standard 2C-2D PIV has been successfully applied in industrial wind tunnels.
- The application of 3C-2D PIV is close to routine application.
- It could be demonstrated that PIV provides high quality spatial information.
The temporal resolution of PIV, which is restricted for application in airflows due to technological limits, must be improved.

Multi-plane stereoscopic PIV (2 x 3C-2D PIV) allows access to the spatio temporal statistics of the flow field.

Full 3C-3D (holographic) PIV is still subject of fundamental research.

4 APPLICATION OF PIV IN HIGH SPEED FLOWS

First applications of PIV have already shown that difficulties appear to provide high quality seeding in high speed air flows compared to applications in water flows or in low speed air flows. The problems are similar to those, which are faced when applying Laser Doppler Velocimetry in such flows. High-speed airflows require small tracer particles in order to minimize the velocity lag. However, by decreasing the particle size the light scattered by the particles will be reduced considerably. Thus, a modern high power Nd:YAG pulse laser is necessary for the recording of tracer particles with a diameter of one micron or less.

4.1 Velocity lag of tracer particles

The tracer particles for all of our PIV experiments have been generated by means of Laskin nozzles. Pressurized air, injected in olive oil, leads to the formation of small oil droplets. The aerodynamic diameter of the olive oil particles is about 1 µm. It is well known from LDV measurements in large wind tunnels and in high speed flows, that the size and the distribution of the tracer particles may change during the travel from the aerosol generator to the seeding device in the settling chamber of the wind tunnel and, finally, to the test section, where the measurements take place. It is therefore advisable, to provide information about the particles and especially about the velocity lag directly form the observation area. The result of our examination of this problem is presented in Figure 5. The u-component of the instantaneous flow velocity along one line of a PIV recording of a flow field with embedded shock is plotted. The instantaneous flow velocity u drops from 359 m/s in front of the shock to 317 m/s within a distance of 8 mm. The real extent of the shock (∼10⁻³ mm) cannot be resolved due to the finite size

Figure 5: Comparison of the experimental and theoretical (dashed line) result for the change of the u-component of the instantaneous velocity vector along a line in the flow field about a bluff cylinder when crossing a shock.
of the interrogation spot (≈ 2 - 3 mm diameter, when projected back into the flow field, indicated as circles in Figure 5). However, a calculation of the velocity lag of particles with a diameter of 1.7 µm, carried out according to the theory as described by Thomas yields a similar relation between velocity and distance as measured with PIV (compare dashed line in Figure 5). This shows that it does not make much sense to utilize tracer particles with a diameter much smaller than 1 µm for this experiment, because of the fact, that during the evaluation of the PIV recording the velocities are averaged within each interrogation spot. Smaller tracer particles would be necessary only, if a higher spatial resolution in the vicinity of the shock would be required.

4.2 Aerosol generator for seeding of high speed flows

Another problem appearing when seeding high speed flows is the concentration of tracer particles. A much larger volume must be seeded for PIV than for LDA as the flow velocity is not only measured at a single point but in a whole plane. Moreover, at PIV there should be no gaps in the seeding, as this would lead to data dropout in the instantaneous velocity field. It is known from simulations of the PIV evaluation process, that typically 15 particle images per interrogation spot are essential for a high quality evaluation. In order to keep constant the number of particles per PIV recording, more particles have to be added to the flow with increasing flow velocity. Thus, a powerful aerosol generator is required for transonic flows. For our experiments we have utilized several Laskin nozzles in parallel. This proved to be sufficient to seed a large stream tube surrounding the model and the observation area. Finally we could attain a high and homogeneous density of tracer particles of the order of ≈ 4 particles/mm³ (this corresponds to ≈ 30 particles/interrogation spot) during our experiments in transonic flows.

4.3 NACA0012 profile in transonic flow

More than 10 years ago first experiences with the application of the PIV technique in transonic flows in a wind tunnel were gained, when investigating the flow field around a NACA0012 airfoil in a blow down wind tunnel at DLR Göttingen. The NACA 0012 airfoil had a chord length of 20 cm. The Reynolds number, based on the chord length and the free stream flow velocity is Re = 3.4 × 10⁶. Back in the 90’s the photographic recording technique and image shifting has been employed. The time delay between the two laser pulses was 4 µs. The size of the observation field is 23 × 16 cm². The instantaneous flow velocity field above the NACA 0012 airfoil is presented in Figure 7.
for an angle of incidence of $\alpha = 5^\circ$. The flow velocity ranges from 280 to 520 m/s. A reference velocity of $U_{\text{ref}} = 311$ m/s has been subtracted from all local velocity vectors in order to enhance details of the flow field. The size of this regime increases with angle of incidence. At $\alpha = 5^\circ$ the supersonic flow regime is terminated by a strong shock. The main problems at the application of PIV in this investigation can be clearly seen in Figure 7: no illumination at left and right side of observation area due to insufficient laser power and no data close to surface of model due to reflections.

### 4.4 Transonic flow field at a trailing edge model of a turbine blade

Another example of the application of PIV in transonic flows is presented in Figure 8. The interaction of the transonic flow field at the trailing edge model of a turbine

![Figure 7: Instantaneous velocity vector map of flow field above NACA0012 airfoil at $M_{\infty} = 0.75$ and $\alpha = 5^\circ$.](image1)

![Figure 8: Instantaneous velocity vector map of flow field at $M_{\infty} = 1.27$ and 1.4% mass flow of coolant air, ejected out of the trailing edge of the plate.](image2)
blade and the mass flow of cooling air ejected out of the trailing edge has been investigated. The instantaneous velocity vector field has been recorded at $Ma = 1.27$ and 1.4% mass flow. Expansion waves and terminating shocks can be clearly seen. The main problems at the application of PIV in this investigation are: no data directly above the plate due to shadow, no data at outlet of cooling air due to strong density gradients (which results in defocused particle images).

### 4.5 Transonic flow field above OAT 15 profile in S2Ma wind tunnel

Most of the progress made by the PIV technique in the past ten years is due to the technological progress made at lasers (much more laser power available), video technique (instead of photographic technique) with modern cooled CCD sensors of high sensitivity, and much faster computers with larger memory. Thus, it is possible today to capture several hundred PIV recordings within a few minutes, to evaluate a single recording within a few seconds automatically and to capture up to 1 Terabyte of data within a wind tunnel campaign of a few days. However, the special problems for PIV in high-speed flows have not yet been solved: generation and distribution of particles, velocity lag, reflections of the light on the surface of the model, limited optical access etc.

![Figure 9: OAT 15 wing profile in ONERA S2Ma transonic wind tunnel.](image)

In order to study these problems in some more detail, a demonstration of the possibility of using 2D (planar) PIV in an industrial large transonic wind tunnel to investigate problems of interest around realistic aircraft geometries has been performed in the frame of the EUROPIV 2 project. The PIV tests have been carried out in close cooperation between the PIV teams of ONERA and DLR. The test facility chosen was the ONERA S2Ma transonic wind tunnel (rectangular test section 1.77 m high and 1.75 m wide) with the swept transonic OAT15 wing (half model, wingspan 1.28 m, mean aerodynamic chord length 0.35 m) installed (see Figure 9). The problems associated with limited optical access in the test section of a transonic wind tunnel can best be understood, when studying the folded arrangement of the laser light sheet which is required to generate the light sheet in the test section (Figure 10). It is clear that it is quite difficult to adapt such an arrangement to any desired observation area. The seeding system as described above, generating particles of a diameter of 1 µm, two
Nd:YAG lasers with 2 pulses of 200 mJ each, and a cooled CCD camera of high sensitivity (in a pressurized housing) have been employed during this investigation.

Figure 11 shows a picture of the tracer particles at $Ma = 0.82$ taken with the CCD camera. A sufficient number of tracer particles can be detected, however a strong reflection appears at the surface of the model, which brings problems at the evaluation of the recording. (Using black color or tape this could be considerably improved in the meantime). As described above, from two of such pictures recorded within an interval of a few microseconds the velocity vector field can be determined.

As an example of the kind of results obtained during this test, Figure 12 shows the instantaneous (left; captured within a few microseconds) and for comparison the averaged (right) velocity vector field above the OAT15 wing at $Ma = 0.82$ and an angle of incidence of $\alpha = 4.5^\circ$. The structure of the shock can be clearly seen. For completeness, Figure 13 shows the averaged velocity vector fields at $\alpha = 0^\circ$ (left) and $\alpha = 4.5^\circ$ (right). As compared to schlieren pictures, PIV provides not only the position of
the shock but also gives quantitative data about the instantaneous and averaged velocity field.

5 CONCLUSIONS

Though the progress made at the application of PIV in high speed flows is smaller as compared to low speed flows, successful applications of standard 2C-2D PIV in industrial transonic wind tunnels have been performed in the last years in S2 in Modane as well as in HST in Amsterdam as in TWG in Göttingen. PIV recordings with high quality spatial resolution could be obtained. 3C-2D (stereoscopic) PIV still needs development to become fully operational in transonic wind tunnels. Still to be solved are problems with optical access, reflections and calibration in confined flows at walls. PIV systems must become more compact, smaller and modular for use in transonic wind tunnels.

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