Recent Applications of Particle Image Velocimetry to Flow Research in Thermal Turbomachinery

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Abstract: During the past decade particle image velocimetry (PIV) became a versatile tool in the investigation of flow fields in turbomachinery. In this overview a short summary on recent applications of PIV in these machines is given, with a focus on rotating turbine and compressor test rigs and the developments within the PivNet network funded by the European Union. Several topics discussed during the PivNet workshops are addressed. To summarize the capabilities of PIV in thermal turbomachinery, the application of PIV to flow investigations in two test rigs is presented. The first one is a transonic turbine operating at 10 600 rpm with 24 stator and 36 rotor blades at Graz University of Technology, Austria, and the second is a centrifugal compressor with a vaned diffusor and an impeller with 13 main and 13 splitter blades rotating at speeds up to 50 000 rpm at German Aerospace Center DLR, Cologne, Germany. At both facilities workshops were organized during the PivNet program.

1 Introduction

Subsonic and transonic regions with a high level of turbulence and a significant level of unsteadiness characterize the flow through modern thermal turbomachinery. The unsteadiness in the flow is related to the relative motion between rotor and stator, with rotor blade passing frequencies up to 20 kHz and above. In multistage axial turbomachinery the unsteady mixing of wakes from stator and rotor blades during rotor-stator motion results in a complex three-dimensional (3-D) flow field, especially when shock systems are present being reflected by passing blades.

The trend for turbines is towards higher efficiency at constant and possibly decreasing costs per kW shaft power. Advanced 3D aerodynamic design and higher cycle temperatures and pressures tackle the objective of higher efficiency. In order to optimize costs and weight it is advantageous to reduce the number of stages, thus resulting in high-pressure (HP) ratios and transonic conditions for the remaining stages.

The modern compressor has to be compact, of high efficiency and often has to meet operation at variable speed with variable geometry. Surge and stall conditions are of special interest in these machines, with very complex internal flow structures often at extremely high rotational speeds.

To tackle these objectives a number of experiments have been performed worldwide applying various kinds of pressure and temperature sensors (e.g. Sieverding et al., 2000) as well as point-wise laser-optical velocimetry (e.g. Schodl, 1997). On the other hand, the year 2004 marked the 20th anniversary of “particle image velocimetry” (Adrian, 2005), with a number of early applications of PIV to flows related to turbomachines or turbomachinery components (e.g. Paone et al., 1989; Goss et al., 1989; Bryanston-Cross et al., 1992). The break-through for PIV in turbomachinery applications came with the development of digital PIV (DPIV, Willert and Gharib, 1991) and stereoscopic PIV (SPIV, Arroyo and Greated, 1991), with commercial systems and a detailed discussion of the basics of this technique soon available (Raffel et al., 1998). Fast recording of three-component velocity providing ensemble averaged as well as instantaneous data is an advantage of PIV, especially in turbomachinery research with its highly unsteady flows and test rigs that are expensive in operation. Thus, PIV offers a major advance for the experimenter, but is not without disadvantages. Due to the high flow velocities very small tracer particles have to be used and imaged well focused through windows of special design. To overcome these disadvantages a number of planar multiple-component techniques are proposed (e.g. Ainsworth et al., 1997; Roehle et al., 2000; Samimy and Wernet, 2000). The discussion and improvement of PIV as well as its comparison to other measurement techniques used in turbomachinery were objectives to the PivNet thematic network funded by the European Union.

2 Recent flow research in thermal turbomachinery

Most recently, considerable research has been done applying DPIV and SPIV to the investigation of turbomachinery components, especially in a nonrotating environment focusing on the one hand on cooling-flow investigations in models and turbine and compressor blade cascade flows on the other.

Chanteloup and Bölcs (2002) and Chanteloup et al. (2002) combined SPIV with heat transfer measurements and applied this technique to the internal coolant passage of a turbine blade including film-cooling ejection modeled in acrylic glass. Using a similar experimental approach Casarsa and Arts (2005) studied the influence of a high blockage rib-roughened cooling channel, Elfert et al. (2004) investigated the flow through a transparent model of the leading-edge duct, Servouze and Sturgis (2003) used DPIV in a rotating model of a two-pass duct and Uzol and Camci (2001) investigated the wake flow field behind pin fins using DPIV. More recently, Panigrahi et al. (2006) did a more basic study on the heat transfer behind ribs using SPIV. Films ejected from a model settling chamber without and with pulsating cooling flows were studied by Bernsdorf et al. (2006a) and Bernsdorf et al. (2006b) using SPIV, while Yoon and Martinez-Botas (2005) focused on cooling flows ejected into the blade tip clearance using DPIV in a model.

The list of researchers using PIV for flow investigations in turbine blade cascades is much longer and only recent work can be cited in the scope of this article. Recently, Palafox et al. (2005) performed flow measurements using DPIV in the tip gap of a low-speed cascade with moving endwall. In this research the camera observed the light-sheet through a transparent blade tip. Rehder and Dannhauer (2006) used oil-film visualization, heat transfer measurements and velocity fields recorded by DPIV to investigate the turbine leakage flow and the flow in the wall and tip region. Raffel and Kost (1998) discussed the interaction between cooling air ejected from the trailing edge and the shock system forming behind the blade. The authors gave detailed information on imaging particles through a strong density gradient. Vicharelli and Eaton (2006) compared a detailed DPIV study of turbulence in a transonic turbine cascade to numerical results. DPIV and laser vibrometer were combined by Woisetschläger et al. (2003b) to discuss the influence of boundary layer state on vortex shedding from turbine blades. For ensemble averaging the PIV images were sorted by vortex shedding phase obtained from the vorticity calculated from the instantaneous recordings. Instantaneous DPIV recordings were also used by Stieger et al. (2004) to quantitatively visualize wake-induced transition in a turbine blade cascade.

Langford et al. (2005) used a triggered DPIV system to study the effect of moving shocks on a compressor stator flow field. Estevadeordal et al. (2002) and

Zheng et al (2006) focused their research on boundary-layer-based flow-control systems in compressor cascades supported by DPIV data. Due to its strength to record instantaneous as well as ensemble-averaged data, DPIV is often used in experiments controlling boundary layer separation, recently e.g. Canepa et al. (2006) and Cerretelli and Kirtley (2006).

During the last decade PIV was developed and used for rotating flows at subsonic or transonic speeds in several unique testing facilities for turbomachines worldwide. Since these testing facilities are of special interest to the turbomachinery community a more detailed summary of worldwide activities is given in Table 1, focusing on research in axial and centrifugal compressors as well as on turbines done within the last decade.

At the von Karman Institute PIV and DPIV were used by Tisserant and Breugelmans (1997) and Balzani et al. (2000) to measure the flow field in a compressor rotor demonstrating the use of periscope-type light-sheet probes and recording velocities in different radial heights. In an international cooperation Ceyhan et al. (1997), Chana et al. (1997) and Bryanston-Cross et al. (1997) presented a detailed DPIV study in high-pressure single-stage transonic turbines in blowdown facilities located at Massachusetts Institute of Technology, MA, USA and Defense Evaluation and Research Agency, Pyestock, UK. Chana et al. (1997) inserted light-sheet probes into the nozzle guide vanes fitted with optical windows and Ceyhan et al. (1997) used two probes and transparent nozzle guide vanes to illuminate the whole inter-blade passage. Finally, Bryanston-Cross et al. (2000) compared the application of DPIV in this type of machines with other optical flow diagnostics tools.

At Purdue University, Day et al. (1996) successfully applied DPIV to a low-speed two-stage turbine with and without film cooling in five span-wise locations. Further on, Treml and Lawless (1998) investigated the stator-rotor interaction in the same test rig. Gallier et al. (2004) used DPIV to record the influence of the seal air flow on the secondary flows in a low-speed two-stage turbine. Sanders et al. (2002a) and Sanders et al. (2002b) focused on the blade row interaction in a transonic axial compressor and discussed shock reflections at 20 000 rpm using DPIV results, with Papalia et al. (2005) extending this research to offdesign conditions. To address offdesign unsteady aerodynamics including dynamic stall Key et al. (2004) used DPIV to record data in an annular cascade with a motor-driven axial-flow rotor.

At NASA Glenn Research Center, demonstrations of DPIV in a single-stage transonic axial compressor and in a high-speed centrifugal compressor were performed (Wernet, 1997; Wernet, 1999). The results are summarized and discussed in Wernet (2000a), Wernet (2000b) and Wernet (2000c). Recently, Wernet et al. (2005) applied SPIV to record the tip clearance flow in a low-speed four-stage axial compressor.

Gogineni et al. (1997) and Estevadeordal et al. (2000) developed a two-color DPIV system using a 3k×3k sensor to record the flow field in a low-speed axial fan at Wright-Patterson Air Force Base. Focusing on the interaction between vortex shedding from wake generators (stators) and bypassing blades in a transonic axial compressor, Estevadeordal et al. (2001) observed phaselocking of vortex shedding to the bypassing rotor blades due to the strong pressure fluctuations caused in the flow field. A detailed discussion of the results can be found in Estevadeordal et al. (2002). This phaselocking allowed the studies of Copenhaver at al. (2002) at near-stall conditions.

Locking of vortex shedding to the rotor-blade movement was first predicted by Sondak and Dorney (1999) for transonic turbine stages. At Graz University of Technology Lang et al. (2002) found this effect in a transonic single-stage turbine by SPIV. In a more detailed analysis SPIV and a direct recording of density fluctuations by laser vibrometers were combined and Woisetschläger et al. (2003a) showed that shock reflections from the bypassing rotor blades enforce vortex shedding in the these transonic machines. Recently, Göttlich et al. (2006) presented a detailed study of vortex shedding and wake-wake interaction in this turbine stage under fully transonic conditions.

At Kyushu University, Hayami et al. (2002) and Hayami et al. (2004) investigated shock waves and their strong fluctuations in a transonic centrifugal compressor by DPIV in cooperation with industry. The recordings were done in the inducer of the impeller and the low-solidity diffusor.

At University of Karlsruhe, Geis et al. (2002) and Bricaud et al. (2005) recorded data from the preswirl cavity located between stator and rotor in the cooling-flow supply to a turbine rotor. For these experiments a SPIV system and

TABLE 1 Recent flow research in thermal turbomachinery using PIV in rotating test rigs (worldwide activities in chronological order)

Authors	**Institution**	**Experiments**	**PIV technique**
Voges et al. (2007)	German Aerospace Center DLR, Cologne, Germany	transonic centrifugal compressor, 35 000 – 50 000 rpm	DPIV SPIV
Ibaraki et al. (2007)	Mitsubishi Heavy Industries MHI, Japan	transonic centrifugal compressor, 28 700 rpm	DPIV
Wheeler at al. (2007)	Whittle Laboratory, Cambridge University, UK	large scale compressor, 500 rpm	endoscopic DPIV
Porreca et al. (2006) Yun et al. (2006)	ETH Zurich, Switzerland	turbine, 2 625 rpm	SPIV
Liu et al. (2006) Gong et al. (2006) Liu et al. (2004a) Liu et al. (2004b)	Beijing University of Aeronautics and Astronautics, China	axial compressor, 1 200 rpm; axial compressor, 3 000 rpm	SPIV DPIV
Childs et al. (2006) Bricaud et al. (2005) Geis et al. (2002)	Universität Karlsruhe, Germany	pre-swirl air flow, up to 7 000 rpm,	SPIV, endoscopic DPIV
Hayami et al. (2004) Hayamai et al. (2002)	Kyushu University, Japan	transonic centrifugal compressor, up to 18 450 rpm	DPIV
Göttlich et al. (2006) Woisetschläger et al. (2003a) Lang et al. (2002)	Graz University of Technology, Austria	transonic turbine, 9 600 – 10 600 rpm	SPIV
Estevadeordal et al. (2002) Copenhaver at al. (2002) Estevadeordal et al. (2001) Estevadeordal et al. (2000) Gogineni et al. (1997)	Wright-Patterson AFB, OH, USA	transonic axial compressor, 14 000 rpm; axial fan, 2 200 rpm	DPIV
Wernet et al. (2005) Wernet (2000a) Wernet (2000b) Wernet (2000c) Wernet (1999) Wernet (1997)	NASA Glenn Research Center, OH, USA	centrifugal compressor, app. 22 000 rpm; axial compressor, app. 17 000 rpm; 4 stage axial compressor, 980 rpm	DPIV, SPIV
Papalia et al. (2005) Gallier et al. (2004) Key et al. (2004) Sanders et al. (2002a) Sanders et al. (2002b) Treml & Lawless (1998) Day et al. (1996)	Purdue University, IN, USA	transonic axial compressor, 20 000 rpm; turbine, 2 500 rpm	DPIV
Bryanston-Cross et al. (2000) Bryanston-Cross et al. (1997) Ceyhan et al. (1997) Chana et al. (1997)	Warwick University, UK	transonic turbine, 8 200 rpm; transonic turbine, 6 000 – 7 800 rpm	DPIV
Balzani et al. (2000) Tisserant & Breugelmans (1997)	von Karman Institute, Belgium	axial compressor, 3 000-6 000 rpm	DPIV, photographic PIV

an endoscopic DPIV were used. Recently, Childs et al. (2006) gave a conclusion for all internal air system test rigs used in the ICAS-GT2 European research program.

At Beijing University SPIV was developed to record the unsteady flow field in the tip region of a single-stage large-scale axial compressor. In this research the two cameras were mounted on each side of the light-sheet, which illuminated the flow through the observation window in the tip-to-hub direction. A detailed discussion of the optical setup is given by Liu et al. (2006), a discussion on the flow phenomena can be found in Liu et al (2004a) and Liu et al (2004b). Most recently, a DPIV investigation of the rotor-stator interaction was presented by Gong et al. (2006).

At Swiss Federal Institute of Technology ETH Zurich, SPIV in combination with fast response aerodynamical probes was applied by Yun et al. (2006) and Porecca et al. (2006) to investigate leakage flows across shrouded turbine blades and their influence on the flow field downstream the rotors in a two-stage axial turbine.

At the Whittle Laboratory, Cambridge University, Wheeler et al. (2007) presented first results on the interaction between wakes and boundary layers in a large-scale axial compressor obtained by DPIV and hot-wire probe measurements.

A detailed study in the vaned diffusor of a high-speed transonic centrifugal compressor was published by Ibaraki et al. (2007) at the Nagasaki R&D Center, Mitsubishi Heavy Industries. With the help of the DPIV and numerical results the authors discussed the unsteady flow field between shroud and hub.

Most recently, Voges et al. (2007) presented results from the diffusor section in a transonic centrifugal compressor rotating at 50,000 rpm at German Aerospace Center DLR. In this publication first results by SPIV are also shown.

Although not in compressible medium, the work by Uzol et al. (2002a) at Johns Hopkins University has to be mentioned. This refractive-index-matched facility combines rotor and stator blades made of acrylic glass with a working fluid of the same index of refraction, so that unobstructed view is possible for DPIV investigations. Results especially interesting for Turbomachinery research are discussed in Uzol et al. (2002b), Uzol et al. (2003), Chow et al. (2002) and Soranna et al. (2006).

3 Optical Configuration

3.1 General configuration of the PIV system for use in turbomachinery

During the PivNet workshops organized at German Aerospace Center DLR, Cologne, Germany and Graz University of Technology, Austria, live demonstrations of the application of PIV to turbomachinery flows were performed. In Fig. 1, a cut through the transonic test turbine facility (TTTF) at Graz University of Technology is shown, presenting the setup commonly used in these types of machines consisting of a periscope-type light-sheet probe, a sufficiently large optical window and a platform for the SPIV camera system. A second window grants optical access for a laser Doppler velocimeter or a laser vibrometer. In this facility rotating the nozzle guide vane ring rather than traversing the probes adjusts the circumferential position for all measurement systems. Thus the SPIV arrangement is fixed in the laboratory system.

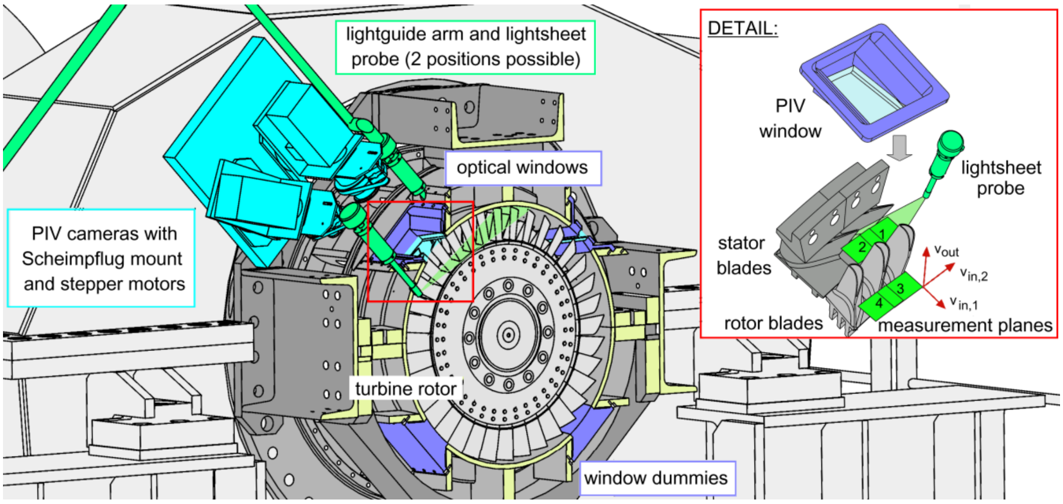


Fig. 1 Experimental setup for SPIV at the transonic test turbine facility (TTTF) at Graz University of Technology (one-stage configuration). The exhaust part was cut off for better visibility. The *detailed view* shows the two light-sheets used and the in-plane and out-of-plane components recorded by SPIV, v_{in} and v_{out}. The optical window is a plane-concave quartz glass for the PIV (upper left window) and a plane quartz glass for laser Doppler velocimetry (upper right window).

3.2 Stereoscopic PIV

In rotating axial machinery, velocity data are usually provided in terms of axial, circumferential and radial velocity, so the yaw and pitch angles of the flow can be easily obtained. Only SPIV allows the calculation of these components from the in- and out-of-plane velocities recorded within the light-sheet plane. On the other hand optical access into high-speed turbomachines is limited due to structural reasons. Depending on the maximum angle between the two cameras the sensitivity of the out-of-plane component is usually less than that of the in-plane components. This sensitivity can be described in terms of sensitivity vectors (e.g. Naqwi, 2000) or as a first-order approximation by the tangent of the half-angle between the two camera axes (e.g. Samimy and Wernet, 2000). Since in most turbomachinery applications curved windows are used, careful calibration of the system is needed using calibration targets in the light-sheet position (e.g. Scarano et al., 2005), with (Willert, 1997) or without (Soloff et al., 1997) image dewarping. Based on the findings of Willert (1997) a misalignment of the calibration target might lead to an artificially increased out-of-plane component especially in the presence of strong velocity gradients (shocks). Lang et al. (2002) discussed this effect for the transonic flow through a turbine. Wieneke (2005) presented a self-calibration correction scheme for SPIV application. To overcome this problem of limited angle of view, some authors propose a combination of PIV and Doppler global velocimetry (DGV), e.g. Wernet (2004) and Willert et al. (2006) or to combine PIV and digital image plane holography DIPH (Arroyo, 2006).

3.3 Seeding

A uniform seeding of a sufficiently high concentration is essential for PIV. Depending on the mass flow seeding is provided globally or locally by an injection tube or multiple jets. Since the tracer particles act as low-pass filter to the turbomachinery flow velocity data, extremely small particles must be used when transonic flows or high frequency flow phenomena are to be observed (Mei, 1996; Woisetschläger et al., 2003b). Various types of nozzles and atomizers, often in combination with cyclone separators, are commercially available and used in high-speed flows (Schrijer et al. 2006). In the test rig shown in Fig. 1 a PALAS AGF 5.0D aerosol generator (PALAS GmbH, Karlsruhe) injected DEHS oil droplets 500 mm upstream the turbine stage. The seeding pipe with an inner diameter of 7 mm was mounted in the rotateable part of the casing and its end extended perpendicular to the flow direction in tangential direction to the annular channel. To spread the seeding uniformly this end of the pipe was equipped with 7 rows of drilled holes distributed uniformly over the diameter along a length of 100 mm (hole diameter 1.5 - 1.8 mm, 140 holes, closed pipe end).

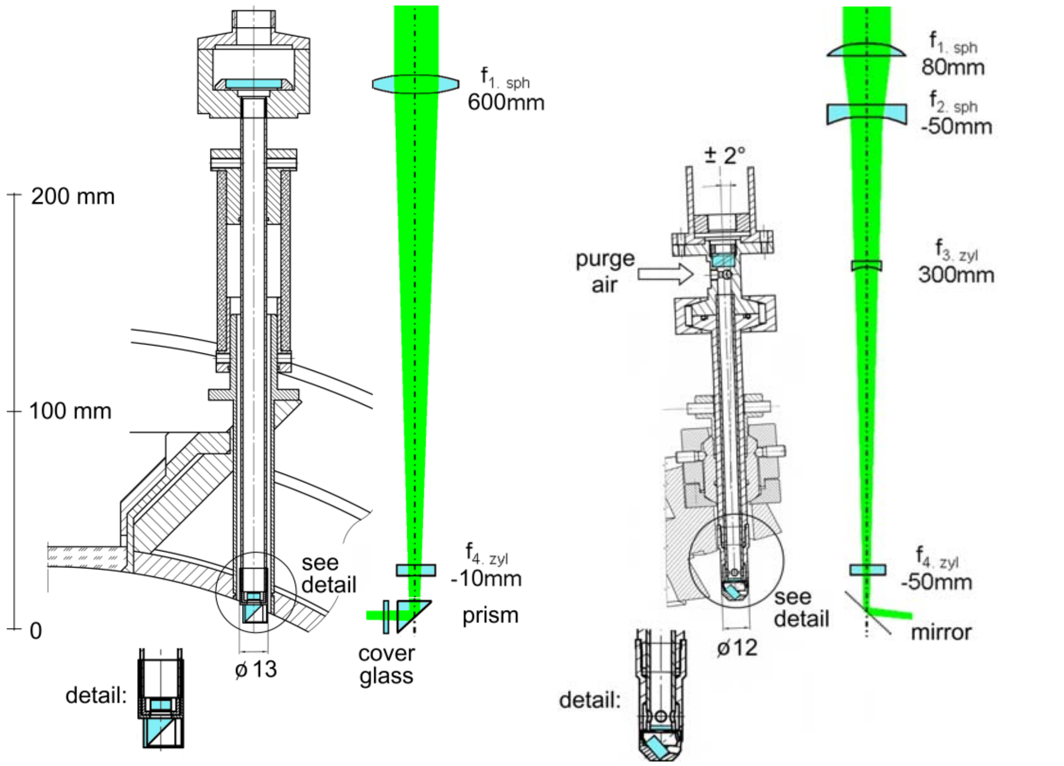
While diffraction effects associated with the chosen aperture dictates the particle image size, it has to be kept in mind that small particles scatter less light. At the limit of detectability insufficient particle image size will lead to “peak locking” effects during sub-pixel interpolation in the evaluation (Raffel et al., 1998). The potential of nanospheres of sufficient size but smaller density was also discussed during the PivNet workshops, although this technology is not ready yet.

3.4 Light-sheet delivery

In most turbomachinery applications a periscope-type light-sheet probe is used to deliver the light-sheet. The two designs used at Graz University of Technology and German Aerospace Center DLR, Cologne are shown in Fig. 2. The first one (Fig. 2a) is of basic design combining a spherical lens with a cylindrical lens, with a cover glass protecting the optics. All elements are clamped and glued using a three-component high-temperature resin (R&G Faserverbundwerkstoffe GmbH, Waldenbuch, Germany). Due to the curvature of the casing the probe towered only slightly into the flow and was inserted in the downstream section of the flow (see Fig. 1). To avoid any intrusion effect Liu et al. (2006) proposed direct illumination through the window section with the two cameras arranged on opposite sides of the light-sheet, alternatively Estevadeordal et al. (2005) developed a fiber-optic system for turbomachinery applications. The probe shown in Fig. 2b is a DLR in-house development and allows also an angular alignment of the periscope. The periscope is purged with compressed air to cool and protect the delicate optics.

3.4 Data recording

In turbomachinery applications the rotating shaft provides the trigger for the PIV system. Different stator-rotor positions are realized with different trigger delays in the PIV acquisition software. Using this trigger signal, ensemble averaging of data for each of the different stator-rotor positions investigated can be performed. Woisetschläger et al. (2003b) used the vorticity in the instantaneous recordings of a stator wake to sort and ensemble average the recordings without trigger signal in order to investigate the shedding process for different boundary layer states.



a **b**

Fig. 2 Two different light-sheet probes used for PIV. **a** shows a periscope probe used at Graz University of Technology, **b** was developed at German Aerospace Center DLR, Cologne, Germany (Image courtesy of M. Voges, DLR, Cologne, Germany).

Due to the small dimensions of turbomachinery blading, the high laser power used and the high sensitivity of the cameras, light reflections might cause problems. In the setup shown in Fig. 1, the inner and outer walls and the blades were covered with a matt black paint to minimize reflections. To cover single reflections fluorescent dye was used when the machine operated in the moderate temperature range (e.g. red Edding® markers). Since the flow through a turbine is highly directional with only the secondary flow effects, vortex shedding and flow interactions being of special interest, an image shifting technique was applied in the main flow direction (up to 11 pixel). In both applications presented here background images (without seeding) were recorded for all stator-rotor positions and subtracted from the recordings (with seeding). Westerweel (2000) gives a theoretical analysis of the measurement precision in PIV.

During the PivNet meetings the application of high-speed camera systems was discussed (e.g. Schröder et al. 2005). There was a general agreement that in the periodic turbomachinery flows with a trigger signal available high-speed PIV is not necessarily needed. On the other hand these system might significantly decrease the measurement time needed, what is of special interest in short-duration test facilities.

4 Results

To summarize the capabilities of PIV in thermal turbomachinery, the results from two demonstrations of PIV to flow investigations in thermal turbomachinery are presented. The first one is a transonic turbine operating at 10 600 rpm with 24 stator and 36 rotor blades at **Graz University of Technology, Austria**. The results of SPIV recordings at midspan are given in Figs. 3-5. For each of the six stator-rotor positions investigated, approximately 180 recordings (dual frame) were acquired (1280×1024 DANTEC 80C60 HiSense and DANTEC FlowMap 1500). Here, the trigger delays were chosen to realize six stator-rotor positions within one blade-passing period, in order to record all data within the same rotor blade pitch. Thus, manufacturing precision does not influence the measured shock positions. A cross-correlation technique with 64×64 interrogation area size and 50 % overlap was applied to the recordings resulting in the single vector fields. A 2D-Gaussfit in a 3×3 Pixel matrix was used for sub-pixel resolution. The single vector fields were post-processed using a peak-height ratio validation, a range validation and a moving-average filter applied to a 5×5 vector matrix. Due to the fact that the vortex shedding from the trailing edge of the turbine blades contains boundary-layer fluid with little seeding the uncertainty in the estimation of the mean value of velocity might increase in these areas.

When looking at the ensemble-averaged velocity in Fig. 3 one can identify a pronounced shock system behind the stator blades (e.g. A and B in Fig. 3). The bypassing rotor blades modulate this shock system and the wakes behind the stator. Shock reflections by the rotor blades alter the yaw angle. In Fig. 4 this interaction can be seen when the yaw angle is plotted, calculated from the axial and circumferential velocities. For the same stator-rotor positions Fig. 5 gives the vorticity calculated from the axial and circumferential velocities. The shock reflection impinging at the stator blade boundary layer triggers vortex shedding in Fig. 5d. Seven phases of vortex shedding during one period of blade passing can be observed. This means the vortex-shedding frequency is about 40 kHz. A detailed comparison with interferometric measurements indicated that the tracer

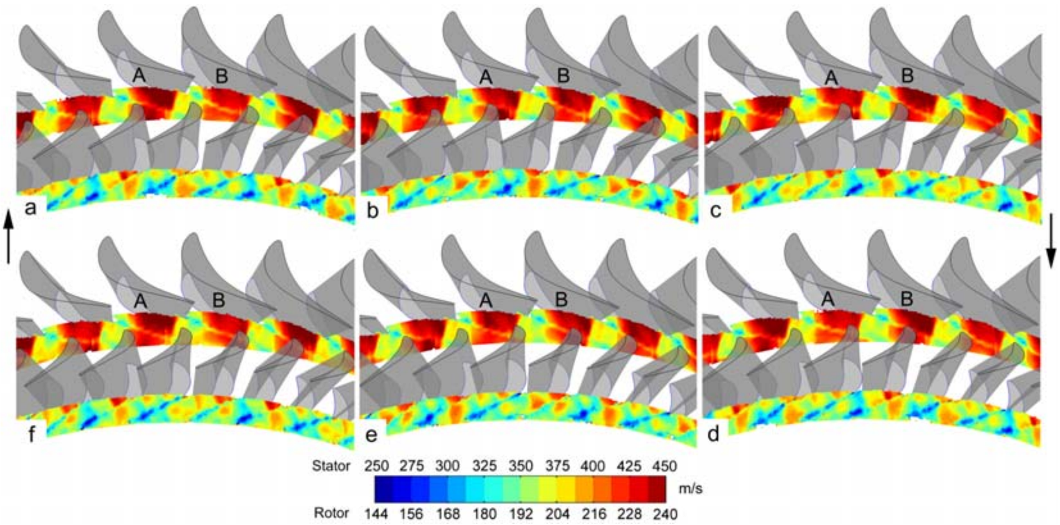


Fig. 3 a-f Ensemble-averaged velocity recorded by SPIV for six stator-rotor positions at 10 600 rpm, recorded in the transonic turbine shown in Fig.1. *A* and *B* indicate two stator blades.

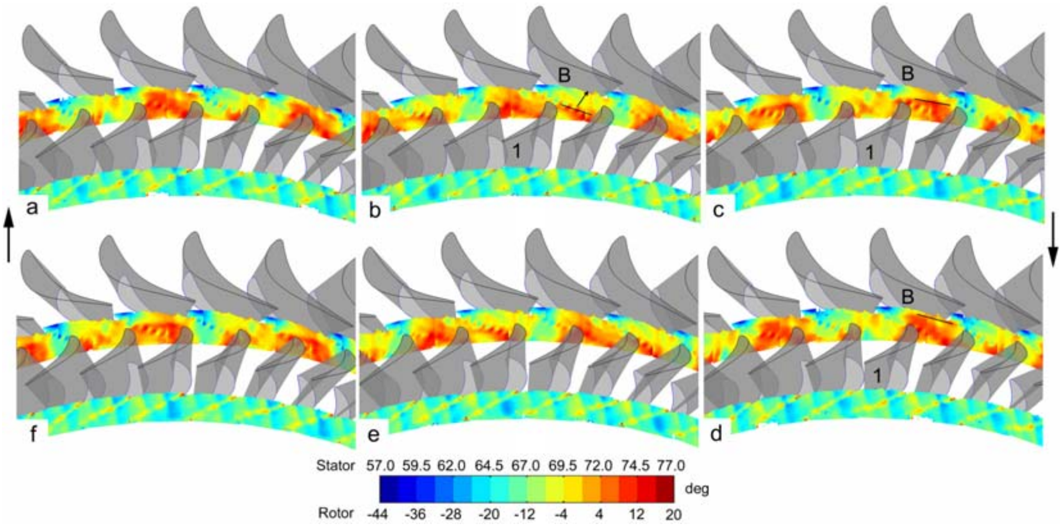


Fig. 4 a-f Ensemble-averaged yaw angle recorded by SPIV (see Fig. 3 for velocity). *B* indicates a stator blade, *1* a rotor blade. The single *line* in **b-d** marks the shock reflection.

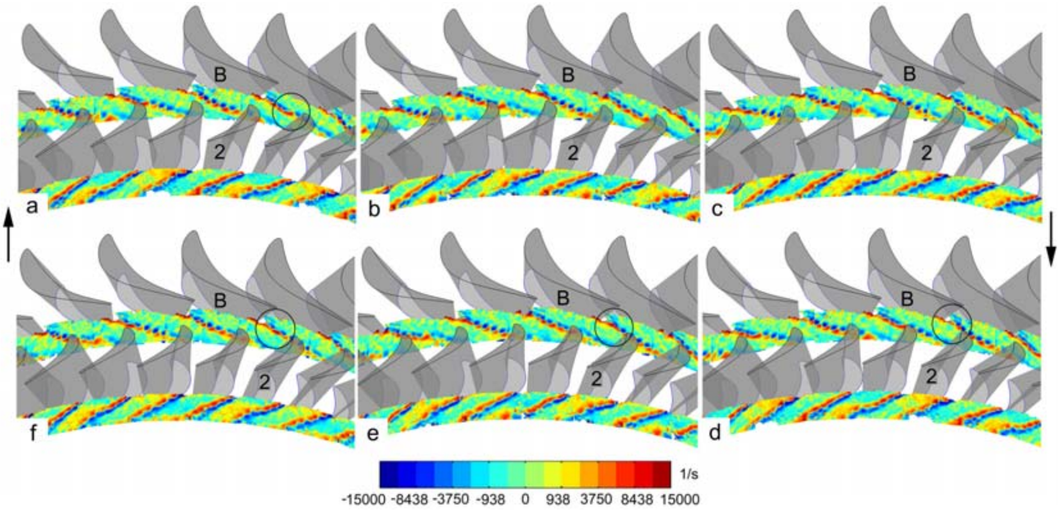


Fig. 5 a-f Ensemble-averaged vorticity recorded by SPIV (see Fig. 3 for velocity). *B* indicates a stator blade, *2* a rotor blade. The circles in **d, e, f, a** mark vortex shedding enforced by the shock reflection in Figs. 4b-d. Behind blade *2* vortex-vortex interference is visible in **a-f**.

particles used started to act as low-pass filter at about 80 kHz. Therefore, only the first harmonic of the vortex movement can be found in the PIV results. On the other hand, PIV provides the unique possibility to investigate the interaction between shocks, shock reflections, vortex shedding and wake-wake interaction in these turbulent and transonic flows. Further discussion of the results can be found in Göttlich et al. (2006).

The second demonstration from which results are presented is a centrifugal compressor with a vaned diffusor and an impeller with 13 main and 13 splitter blades rotating at speeds up to 50 000 rpm at **German Aerospace Center DLR, Cologne, Germany**. Evaluation of the PIV image data was performed after pre-processing with high pass filter, subtraction of background images and masking image areas without velocity information (e.g. diffuser casing or window support). A correlation algorithm with multi-grid option resulting in a final 32×32 pixel interrogation window with 50% overlap was used. The size of single interrogation areas in the light-sheet plane achieved during processing was 0.5×0.5 mm, potentially corresponding to flow structures passing at frequencies up to 1.4 MHz at a velocity up to 700 m/s. Here the size of the particles has an important influence on the obtained velocity data. The particles used (oil droplets, below 1 μm) behave like a low-pass filter with a cut-off frequency of 100 kHz. Given a blade passing frequency around 20 kHz, this implies that only large-scale structures are faithfully captured, while smaller scales are damped out.

In the PIV test sequence phase-resolved measurements were carried out using eight phase angles per main-splitter passage. As the impeller exit flow was not expected to be symmetric between main-splitter and splitter-main blade passages, the number of phase angles was doubled. The resulting 16 phase angles allow for detailed flow investigations related to one complete main-splitter-main passage. For each angle 180 PIV recordings were averaged (ensemble averaging).

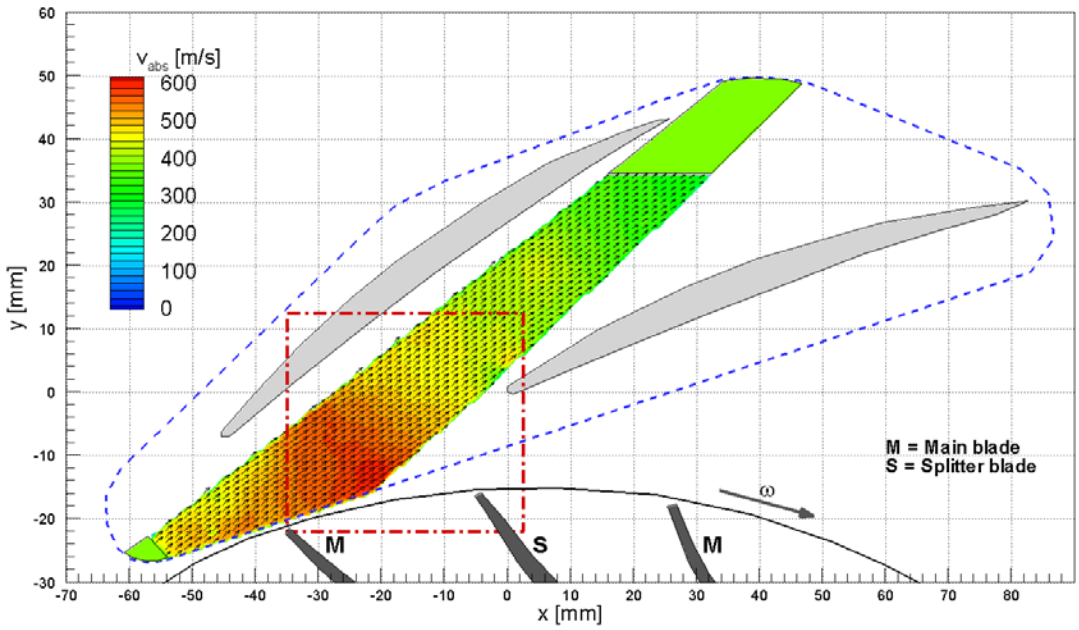


Fig. 6 Ensemble averaged velocity recorded by PIV in the diffuser passage of a transonic centrifugal compressor at 50 000 rpm for the rotor position shown. The *dashed blue line* indicates the window section. The recording was done at the German Aerospace Center DLR, Cologne, Germany (image courtesy of M. Voges, DLR, Cologne, Germany).

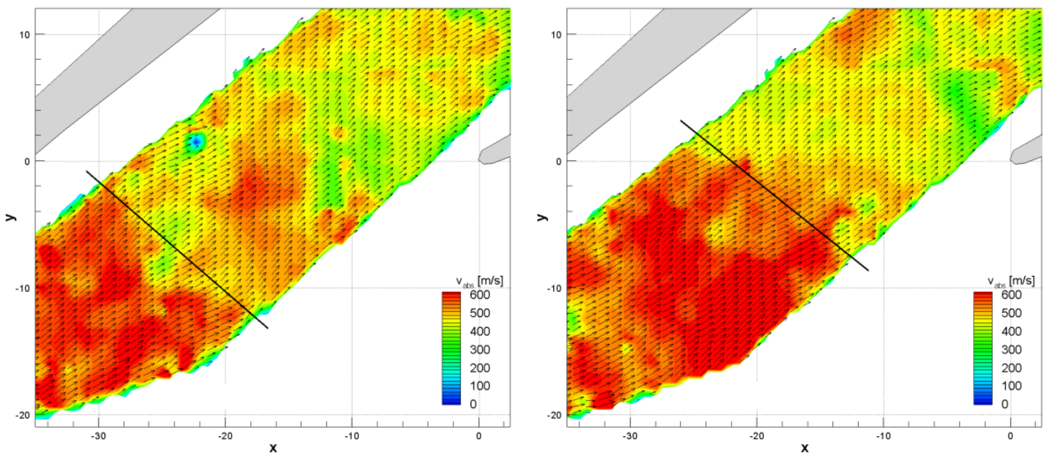


Fig. 7 Instantaneous velocity recordings by PIV for the same rotor-vane position as shown in Fig.6. The *line* indicates the shock position. A strong shock oscillation is observed between the *left* and the *right* image. The recording was done at the German Aerospace Center DLR, Cologne, Germany (Image courtesy of M. Voges, DLR, Cologne, Germany).

Following the transient diffuser passage flow while the impeller passes by, the flow structures emerging from impeller blades become visible. At a rotational speed of 50 000 rpm the impeller blades were passing at a frequency of 21.74 kHz. Based on the exit speed of 580 m/s such frequencies become visible as structures of 26.7 mm size. Such structures can be identified in the velocity recording in Figs. 6 and 7. While Fig. 6 gives the ensemble-averaged velocity, Fig. 7 plots two instantaneous recordings, showing a significant oscillation of the shock front for the same impeller position. Further discussion of the results can be found in Voges et al (2007).

5 Conclusions

Today, particle image velocimetry is established as a powerful tool in recording unsteady as well as ensemble-averaged velocity data from fast-rotating turbomachinery. However, some details of the basics of this technique have to be taken into account to obtain quantitatively correct data. These details and future developments were discussed during the PivNet workshops with mutual visits between the turbomachinery labs involved in this program. Additionally, the presentations and the reports had been made available to the European turbomachinery community through the European strategic research projects all of us participated in.

Throughout the workshops there was an ongoing discussion as to which structures can be observed within the turbomachinery flow field by the PIV technique. In most turbomachinery applications a size of 0.5×0.5 – 1×1 mm for the single interrogation areas was achieved. Depending on the flow speed this correlates to frequencies up to 1.4 MHz, compared to fast response aerodynamic probes a remarkable good result. On the other hand, the fact that PIV spatial resolution is reduced to corresponding frequencies below 100 kHz by the inertia even of small particles, was generally accepted and has to be mentioned in scientific work where fast-changing flow phenomena are observed. The development of novel tracer particles with lower density has to be watched carefully by the turbomachinery community.

Most turbomachinery applications are characterized by difficult optical access to the areas of interest. Especially when the windows are highly curved or perspective viewing cannot be neglected, ray tracing and unwarping of images previous to the correlation procedure was recommended, including an estimation of the directional sensitivity within the light-sheet. The difficult optical access also limits the use of SPIV and recommends the combination with other techniques such as DGV or the development of miniaturized systems. Additionally, any combination of techniques improves physical understanding of flow phenomena (i.e. DPIV in combination with pressure-sensitive paint, interferometry, surface temperature by infrared imaging or thermoliquids).

High-speed capabilities are welcomed, but mainly in order to speed up the measurements. Recordings sorted by the phase of the rotor are certainly sufficient to investigated stator-rotor interaction and correlated unsteady effects in turbomachines.

Summarizing, above-mentioned new developments in the PIV technology will also break new grounds in turbomachinery flow research. The PivNet triggered these developments.

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