Investigation of a low pressure turbine blade by means of simultaneous optical velocity and pressure measurements

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ABSTRACT
The combined application of state-of-the-art optical velocity and pressure measurements using both the Particle Image Velocimetry (PIV) and the Pressure-Sensitive Paint (PSP) measurement techniques simultaneously, was assessed with respect to the difference to their individual usage. Typical drawbacks of the combined use, like the PSP contamination with PIV seeding fluid, the flare of the PSP layer in the near-wall PIV regions or the interference of different wavelengths are addressed with respect to their impact on the measurement accuracy. A low pressure turbine (LPT) blade was investigated at a Reynolds number of Re₂₄₈ = 120,000. The flow topology around such an airfoil features challenges for both measurement techniques, e.g. high curvature streamline deflections, thin laminar separation bubbles or strong shear layers. The results show, that a combined application of both techniques is basically possible with moderate impact on the measurement uncertainty. It was shown, that the resolution of the thin laminar separation bubble was not possible with classical PIV window-correlation techniques. Advanced Particle Tracking algorithms gave an impression of the dimension but could not fully characterize it.

1 Introduction
As common forecasts predict a significant increase of the world wide air traffic in the next years, it is very important to improve the efficiency of airplanes and jet engines to keep the environmental and financial impact as small as possible. Weight reduction is one possibility to improve the efficiency of jet engines. To reduce weight and cost of low pressure turbines by reducing the blade’s chord, high lift airfoils such as the T161 have been investigated and applied in recent years, see e.g. Gier et al. (2010). Due to the high loading, such profiles are prone to flow separation on the suction side for low Reynolds numbers. Compared to a conventional low pressure turbine (LPT) airfoil, the Zweifel coefficient of this blade is approximately 25% higher as shown in Gier et al. (2010). Curtis et al. (1997) showed that the flow behavior on the suction side is responsible for the major part of the blade losses. Due to the high aerodynamic loading, the airfoils suffer from strong flow separation effects on the suction side occurring as a laminar separation bubble (LSB) especially at low Reynolds numbers. The authors in Niehuis and Mack (2014) or Martinstetter et al. (2010) investigated the effect of various active and passive kinds of boundary layer control mechanisms on the manipulation of the LSB and the development of the boundary layer. They showed that these control mechanisms can reduce the total pressure losses of the T161 blade by up to 50% or 35% for unsteady and steady manipulation, respectively. Nevertheless, due to the low wall-normal expansion, the LSB topology has not been worked out yet. To analyze this in detail, advanced measurements techniques with high spatial resolution are required. The knowledge gained with these advanced methods is essential to establish a robust relation between the blade aerodynamics and the total pressure losses of the profile. The
detection and distinction of loss mechanisms gives the opportunity for further improvement of the efficiency of low pressure turbines.

Here, the application of state-of-the-art optical velocity (Particle Image Velocimetry - PIV) and pressure (Pressure-Sensitive Paint - PSP) field measurements techniques with high spatial resolution is favorable to resolve the desired flow quantities. The stand-alone application of both these techniques has exemplary been shown e.g. by the authors in Konrath et al. (2008). A real simultaneous measurement of the velocity and pressure in the flow field has been demonstrated by Abe et al. (2004) based on the use of pressure-sensitive tracer particles for PIV. The work presented here addresses the simultaneous measurement of the flow velocity and the surface pressure around an LPT blade by means of a standard 2D2C-PIV and a PSP system using a commercially available bi-luminophor coating. The experiments were carried out in a joint project involving the Institute of Jet Propulsion and the Institute of Fluid Mechanics and Aerodynamics both domiciled at the Bundeswehr University Munich.

2 Experimental Setup and Methodology

2.1 High-Speed Cascade Wind Tunnel

The experiments were performed in the High-Speed Cascade Wind Tunnel (HGK) of the Institute of Jet Propulsion. The facility, as sketched in Figure 1, can be used for the characterization of linear compressor and turbine blade cascades at turbomachinery in-flight conditions. A detailed introduction of the facility is given in Sturm and Fottner (1985). A 6-stage axial compressor is driven by a 1.3 MW electric motor. The compressed airflow is guided in a closed channel. Further downstream, the flow is conditioned first in a cooling system and homogenized by several screens and honey combs in the settling chamber. Inside the nozzle, typical inlet turbulence levels in the range of 2 - 8% can be generated using passive grids (approx. 4 % in the present study). The installation angle of the turbine cascade in the test section at the outlet of the duct can be varied in order to provide arbitrary incidence angles. For the simulation of real in-flight Reynolds numbers, major parts of the facility are placed inside a vacuum tank with a diameter of 4 m which can be operated in a pressure range from 110 kPa down to 4 kPa. Continuous experiments at Mach numbers up to \( \text{Ma} = 1.1 \) can be performed over

![Fig. 1 Main components of the High-Speed Cascade Wind Tunnel (HGK) operated by the Institute of Jet Propulsion at the Bundeswehr University Munich.](image)
The low pressure turbine blade “T161” was designed by MTU Aero Engines AG Munich as a rear-loaded high lift turbine blade. For the experiments presented here, a cascade consisting of seven 2D airfoils was mounted in the HGK test section. Divergent side walls as well as tail boards were applied. The blade’s aerodynamic design point (ADP) is defined at a theoretical exit Mach number of 0.6 and a Reynolds number of 200,000, based on the chord length (here: c < 70 mm). At design conditions, the flow turning is approx. 110°. The blade height was 280 mm. Both, the PIV and PSP measurements were performed on the center blade at an off-design Reynolds number of Re$_{2,\text{th}}$ = 120,000 in order to promote suction side flow phenomena like laminar separation or laminar-turbulent transition via a separation bubble. The experimental parameters are given in Table 1.

### 2.2 Experimental Techniques and Setup

**Particle Image Velocimetry - PIV**

A laminar separation bubble is expected to develop in the rear part on the blade’s suction side. Standard 2D2C-PIV measurements were performed with two different optical magnifications in order to: a) resolve the flow topology in the rear part of the passage between two blades in the cascade (PIV-1), and b) in order to resolve the laminar separation bubble (PIV-2). Positions and dimensions of the different fields-of-view can be seen in Figure 2. A sub-region of the PIV-2 dataset as indicated by the PTV-frame was analyzed with a state-of-the-art PTV algorithm.

A QuantaRay 400 double pulse Nd:YAG laser with 400 mJ pulse energy was positioned outside of the HGK vacuum tank. The perpendicular access through an optical window into the tank was attended in order to neglect a potential beam displacement due to severe density changes. The PIV light-sheet, which had a thickness of approx. 0.5 mm in the field-of-view (FOV) was located in the symmetry plane of the center blade as indicated on the left in Figure 3. The laser light-sheet was perpendicular to the symmetry plane, as shown in Figure 4.

![Fig. 2 Definition of the field-of-view for the PIV/PTV investigations. The blade section covered with PSP is displayed in gray. The blade dimensions are normalized with the geometrical length of the suction side $s_{ss}$.](image-url)
optics were positioned approx. 1 m away down the blade slightly off the main flow jet. A 5.5 Mpx scientific CMOS camera in combination with a Zeiss Macro objective lens (PIV-1: f = 50 mm; PIV-2: f = 100 mm) were used for PIV imaging. All imaging equipment was mounted inside the vacuum tank and exposed to the low ambient pressure. No obvious effects on the images (e.g. increase of noise, read-out artefacts) were observed within the tested low pressure range. The images were recorded with 8-10 Hz (lower for combined PIV and PSP measurements). A window in the cascade frame enabled the observation from outside the test section at a working distance of about 350 mm. This optical setup led to a spatial resolution of 0.5 mm (PIV-1) and 0.28 mm (PIV-2). The full setup is presented in Figure 3. A summary of the specific parameter for the PIV investigations is given in Table 2.

Pressure-Sensitive Paint – PSP

Pressure-sensitive paint (PSP) is an optical oxygen sensing technique, commonly used for aerodynamic testing. This method is based on the detection of luminescence intensity. O₂-sensitive luminophors are excited with UV radiation and can emit in a longer wavelength band if they did not transfer their excitation energy to a quenching partner like e.g. an O₂ molecule. These luminophors are typically incorporated into a binder material so that they can be easily applied to the test object by using common painting equipment. A luminescence calibration for given ambient pressures constitutes the basic relation $I_0/I = A + B \cdot (p/p_0)$ known as Stern-Volmer relation including the luminophor constants A and B as well as the emitted intensity $I$ and $I_0$. The reference condition (index “0”) is typically the no-flow (or “wind-off”) state, where the pressure is constant and easy to measure. For more information on this non-intrusive pressure measurement technique the reader is referred to Liu and Sullivan (2005).

The measurement blade was coated with a commercially available bi-luminophor PSP which has two luminophors incorporated: a) a pressure-sensitive platinum complex which is sensitive to oxygen, temperature and intensity changes and, b) a complex which is insensitive to oxygen but senses temperature and intensity fluctuations. This second complex is referred to as reference dye. In order to obtain the relevant intensity ratio, two ratios of four intensity images have to be calculated as $I_0/I = (I_{p,0}/I_p)/(I_{ref,0}/I_{ref})$ whereas $I_p$ denotes the intensity of the pressure-sensitive dye and $I_{ref}$ of the reference dye. Both dyes emit in different wavelength bands, separated by appropriate optical filters. This commercial paint is well characterized, see ISSI (2016). Its performance and accuracy even at rough conditions such as in a turbomachinery rotor stage

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**Fig. 3** Experimental setup for the PSP measurements (left) and the PIV measurements (right) around the turbine blade in the test section of the High-Speed Cascade Wind Tunnel of UniBwM.
with a strong surface temperature gradient was already demonstrated, see Bitter et al. (2015). This paint was also chosen because it delivers reasonably accurate results even in the presence of paint layer contaminations as they might be caused by the PIV seeding fluid, see Bitter (2013). The coating was directly applied to the blade without any screen layer in order to prevent a change of the aerodynamic shape and a manipulation of the LSB. For paint excitation, a high-power LED emitting 10 W optical power at 405 nm was operated in pulsed mode. Two 14 bit interline CCD cameras with 11 Mpx frame size were equipped with appropriate filters for intensity signal separation. The camera integration gate was synchronized with the LED pulse duration. The components for the PSP setup are also outlined in Figure 3. Typically, the center blade is free of any instrumentation in order to avoid perturbations especially for the determination of the profile losses. For the campaigns presented here, a blade with six static pressure ports on the suction side was coated with PSP in order to use the pressure tap readings for an in-situ reference. The main PSP test parameter are also outlined in Table 2.

### Table 2 Specific parameters for the PIV and PSP experiments

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<th>combined PIV/PSP measurements</th>
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2.3 Methodology

The experiments were split into three campaigns. The first two campaigns covered the isolated PSP and PIV measurements which serve as a reference. The combined PIV/PSP measurements

![Fig. 4 Timing scheme for the light sources at the combined PIV/PSP measurements; green = Nd:YAG laser for PIV, purple = UV LED for PSP.](image-url)
were carried out afterwards. As the PSP luminophors absorb in a broad wavelength band and, in particular, around the Nd:YAG laser wavelength of 532 nm, a timing scheme as outlined in Figure 4 was applied for the combined PIV/PSP measurements. It ensured the separation of the PIV laser light from the PSP illumination. Each short-pulse PIV illumination of roughly 10 ns was separated by a pulse delay of $\Delta t = 1.8 \mu s$. Both of these pulses excite the PSP coating. The luminescence caused by the laser pulses was allowed to decay for $\tau_f = 50 \mu s$. After the decay, the synchronized LED/camera integration gate started. For the case of the combined measurements, the PSP integration time was set to 100 ms at approx. 8 Hz offering a good trade-off between PSP signal intensity and image recording time for sufficient PIV statistics.

Particle Image Velocimetry - PIV

A data set of 10,000 images was acquired for the isolated PIV measurements in order to have a good statistical convergence. The amount of images was reduced to 1,000 for the combined PIV/PSP campaign. The data evaluation was performed in DaVis 8.2.3 providing state-of-the-art PIV and PTV algorithms, see Kähler et al. (2016). For a high signal-to-noise ratio, the raw PIV images were pre-processed using a moving average subtraction over 21 images followed by a local Gaussian average subtraction over 4 px. For the isolated PIV measurements, the blade was shiny polished in the area where the laser light sheet hits the model surface. Finally, areas of strong reflections or bad light sheet quality were masked out. A multi-pass cross-correlation algorithm with decreasing interrogation window size $W: 64^2 \text{ px} \rightarrow 32^2 \text{ px}$ (50 % overlap) was applied. Due to the strong curvature and hence the strong accelerations around the LPT blade, a low seeding density is expected in the near-wall regions. This expectation was confirmed by means of a 2D numerical simulation at test conditions. A structured grid with 50,000 nodes was generated to resolve the viscous domain up to approx. 5 boundary layer heights. The solution was converged after roughly 1,000 iterations applying the shear-stress turbulence model (SST)
with standard parameter. A rake of 100 inert particles with physical properties of the DEHS seeding fluid ($\rho = 912 \text{ kg/m}^3$, no initial slip) were injected into the numerical solution upstream of the blade. The diameter of the injected particles was varied in the range of 0.1 to 2.0 µm as produced by typical laskin seeding atomizers. Figure 5 shows the steady particle tracks for the different particle diameter (color-coded) whereas only every 5th track is shown. The median diameter of seeding atomizers, which are driven by pressurized air, is around 1 µm as reported in Kähler et al. (2002). Smaller particles obviously tend to follow the strong curvature without being deflected away from the wall. The scattered light of such small particles is too low to be reliably detected with standard PIV cameras. Particles of larger diameter (e.g. 2 µm) suffer from stronger inertial effects. As a consequence, these particles are carried further away from the wall. Anyhow, turbulent fluctuations transport some particles of all different diameters into the near-wall regions.

*Particle Tracking Velocimetry - PTV*

Due to an expected low particle concentration in the boundary layer, a PTV evaluation was performed with DaVis 8.2.3 for a subset of the PIV-2 data as mentioned before. A subset was chosen in order to save evaluation time because the tracking of individual particles in 10,000 double-frame images can be very time-consuming. A 5×5 automatic Gaussian particle fitting was applied for particle position detection. The particles were tracked over 10 neighbors and a search range of max. 50 px with a maximum vector field gradient of 0.4 px/px. Each PTV vector was finally binned on a regular 16×16 px grid representing the same spatial resolution as for the final PIV pass.

*Pressure-Sensitive Paint - PSP*

Data sets of 50 (1000) flow intensity images and 10 (10) no-flow intensity images were acquired for the isolated PSP (and the combined PIV/PSP) measurements, respectively. Prior to the image acquisition, the entire setup as well as the flow was allowed to reach thermal stability for about 20 minutes. The data acquisition for the isolated PSP measurements was performed with 1 Hz. Hence, the absolute measurement time was fairly short compared to the simultaneous tests as discussed later. Directly after a data set was completed, the axial compressor was shut down and the no-flow images were recorded. An in-house Matlab routine was used for data evaluation. It offers state-of-the-art PSP image processing techniques such as sub-pixel image alignment, data projection to 3D grids or in-situ correction. The image data was mapped on a structured 3D grid of the blade using reference markers on the LPT surface and photogrammetry relations. A 1 mm grid spacing was chosen for data representation offering sufficiently high spatial resolution.

The paint was a-priori calibrated on a sample in a calibration chamber. This calibration was applied to the test results to calculate the pressure distribution. The readings from 3 out of 6 surface pressure taps in the region-of-interest were used to apply a linear offset correction $p_{\text{PSP}} = c \cdot p_{\text{tap}}$. The pressure tap measurements were performed with steady 98RK-1 pressure scanners with a 5 PSI measurement range. The measurement uncertainty was ±0.05 % full-scale.

All pressure tap readings were used to calculate the deviation to the PSP results and estimate the PSP measurement uncertainty.
3 Discussion of Results

Velocity field

In Figure 6, the flow topology on the suction side of the LPT blade is compared for the isolated PIV measurements and the combined PIV/PSP measurements, respectively. The isentropic Mach number contour is shown which was calculated from the measured PIV velocity field and the total temperature at the inlet of the test section. All results were ensemble-averaged from 1,000 instantaneous PIV vector fields. A mask blanks out spurious vectors resulting from the edges of the laser light sheet. The flow Mach number was calculated by means of the speed of sound present at the inlet plane ($a_1 = 341$ m/s) and normalized with the blade’s design exit Mach number.

Figure 6 shows the normalized flow Mach number field as calculated with the PTV algorithm from the high resolution PIV-2 data. This data set was only available for the isolated PIV measurements since the PSP flare would also impede the data evaluation here. For this presentation, 10,000 PTV vector fields were ensemble-averaged and binned on a 16×16 px grid. The white arrows represent every flow vector in wall-normal direction and every 20th in the axial direction. The thickness of the boundary layer at the trailing edge was far less than 2 mm. It is evident that the PTV analysis well captures the shape of the boundary layer profile. Unfortunately, the extension...
of the laminar separation bubble could not be clearly examined from the velocity data. The ratio of particles which are entrained into the boundary layer by turbulent fluctuations to that particles which smoothly follow the flow very close to the surface is very small, as expected from the seeding injection into the numerical simulation. Hence, the direction of larger seeding particles (>1 µm) close to the wall is biased and not statistically independent. These particles do not move against the main flow direction as it typically appears in a laminar separation bubble. As a consequence, the flow vectors all have a positive axial component and no backflow is present. The expansion of the boundary layer and the strength of the velocity gradient is well emphasized by the distribution of the turbulent kinetic energy TKE in the lower figure. The classic window correlation analysis of the PIV-2 data set delivered a similarly poor resolution of the near-wall velocity profile as presented in Figure 6 before. The main reason for the spurious evaluation is outlined in Figure 8. The plot reveals the absolute number of detected particles in each 16×16 px bin with respect to the number of recorded PIV images. As obvious, the
concentration of particles close to the surface is low. Even for a data set of 10,000 images there are partly less than 1,600 particles in each bin. This means, there is 1 particle in one bin every 5 images. As expected from the CFD investigation discussed above, regions further away from the wall possess a very high particle density.

**Surface pressure**

In this section, the isolated Pressure-Sensitive Paint measurements are compared to the results of the combined PIV/PSP experiments. An isentropic surface Mach number can be calculated from the surface pressure using Equation (1). The total pressure at the inlet $p_{t1}$ is measured with a pitot probe at the test section inlet. The corresponding value is given in Table 1. In Figure 9, the top view on the rear part of the T161 suction side is presented comparing the normalized surface pressure to the isentropic surface Mach number.

![Fig. 9 Comparison of the isentropic surface Mach number on the rear of the T161 suction side for the isolated PSP measurements (top), the combined PIV/PSP measurements (center) and the difference between both tests (bottom).](image)
Mach number for the isolated PSP and the combined measurements. The main flow is approaching towards the reader and is deflected upwards in this presentation. The relative deviation $\Delta M_{a_{is}} = 1 - \left( \frac{M_{a_{is,PIV+PSP}}}{M_{a_{is,PSP}}} \right)$ between the isolated and the combined results was calculated to clarify the direct influence between both data sets.

$$M_{a_{is,x}} = \sqrt{\frac{2}{K-1} \cdot \left( \frac{p_{is}}{p_{x}} \right)^{\frac{K}{K-1}} - 1}$$

The topology of the Mach number distribution emphasizes a widely symmetrical flow across the width of the test section. The design exit Mach number is well reached from the vicinity of the trailing edge. The outer accelerated regions near the side walls (dark red) are caused by secondary flow effects representing a merged footstep of the horse-shoe vortex, the passage vortex and the corner vortex between the blade and the side walls. A quasi-2D flow is present over roughly ±30 % around the blade’s centerline. Comparing both, the isolated and combined results, the strongest discrepancy occurs close to the centerline. This defect is caused by the laser light sheet which photo-chemically deactivates a number of luminophors in the PSP due to too strong excitation. The strong accelerations in the secondary flow region lead to an intensified agglomeration of tracer particles on the PSP coating. Some particles cannot follow these strong gradients, clash on the surface and are washed away downstream on the blade’s surface. This local contamination of the PSP coating can be reduced and partly compensated by the reference luminophor incorporated into the paint. Nevertheless, if strong contamination occurs (e.g. parts of the trailing edge), the deviation from the isolated measurement significantly increases. Figure 10 gives an impression of the contamination after approx. 50 minutes of testing. It shows the raw intensity ratio images for both, the pressure dye ($I_{p,0}/I_{p}$) and the reference dye ($I_{ref,0}/I_{ref}$). The traces of seeding fluid in the ratio images is clearly visible for regions of strong secondary flow. Compared to the relative difference on the bottom of the previous figure, the impact of the contamination on the measurement accuracy can be quantified. If a combined application of both techniques is favorable, an increase of the PSP measurement uncertainty can be expected. These results show a deviation of ±5 % between the isolated and the simultaneous measurements.

Finally, the PSP measurement uncertainty is assessed in Figure 11 using the 6 pressure tap values as reference which coincide with the PSP coating. In addition, the pressure distribution from the RANS simulation, which was discussed above, is completing the plot. The RMS of the deviation $\Delta M = 1 - \left( \frac{M_{a_{is,PSP}}}{M_{a_{is,tap}}} \right)$ shows a good agreement of both optical measurements with the classical tap measurements. The uncertainty is about 1 percent, slightly higher for the combined PIV/PSP measurements.
Conclusion and Outlook

The simultaneous application of optical velocity measurements using Particle Image Velocimetry (PIV) and optical pressure measurements by means of Pressure-Sensitive Paint (PSP) have been demonstrated successfully. The joint campaign between two partner institutions located at the Bundeswehr University Munich was carried out on MTU Aero Engines’ T161 turbine blade in the High Speed Cascade Wind Tunnel (HGK) at ambient pressure around 12 kPa ($Re_{2,th} = 120,000$) and a moderate exit Mach number. The combination of both techniques makes efficient velocity field and surface pressure investigations possible by saving precious wind tunnel time. The cost for this benefit is: a) a reduced measurement accuracy in the PSP results due to the contamination of the PSP coating as a consequence of the interaction with PIV seeding fluid by approx. ± 5 %, and b) a decreased resolution of the PIV vector field near the PSP coating caused by the flare of the excited PSP layer. Both effects have been worked out and presented in detail.

The individual application of each measurement technique was also demonstrated for the same test case. The goals were: c) the quantification of the flow field as a reference data set for the simultaneous measurements, and d) the resolution of the thin laminar separation bubble in the near-wall boundary layer on the blade’s suction side. The uncertainty of the isolated PSP measurements was around 1 % using classical pressure tap values as reference. The isolated PIV measurements were performed with spatial resolutions up to 0.3 mm. The high turning angle of the turbine blade caused a low seeding density in the near-wall region. The inertial effect and the dependence on the tracer particle size have been demonstrated numerically. Hence, the resolution of the boundary layer by means of PIV was not successful. Anyhow, a Particle Tracking algorithm was capable to deliver good results in this region. It was shown, that some tracer particles are available in the vicinity of the wall but their flow vector may be biased due to their entrainment stimulated by turbulent fluctuations. Unfortunately, the biased flow field impeded an exact localization of the laminar separation bubble. A local seeding of the near-wall region might overcome the lack of particles and increase the statistical independency of the velocity vectors in that region.

\[ \Delta Ma = 1 - \frac{Ma_{b,PSP}}{Ma_{b,tap}} \]

Fig. 11 Comparison of PSP (black lines), pressure tap (square symbols) and RANS surface Mach number (gray line) extracted at the centerline of the T161 blade at $Re_{2,th} = 120,000$. Dimensions are normalized by the design exit Mach number or the chord length $l$, respectively.
Acknowledgements The work was partly performed within the FP7 research project NIOPLEX funded by the European Union under grant agreement GA605151. The authors also thank MTU Aero Engines for the permission to use the turbine cascade T161 for research purposes.

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