Time-Resolved Tomographic PIV of a High-Lift Configuration in an Industrial-Grade Wind Tunnel

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Abstract The present feasibility study demonstrates flow field measurements on the suction side of an airfoil in high-lift configuration under test in an industrial-grade wind tunnel using time-resolved tomographic PIV. The influence of the parameters most relevant to tomographic PIV in industrial wind tunnel environments has been studied. The successful application of this measurement technique takes a significant step towards the necessary scale-up and toughening to bring tomo-PIV from laboratory-scale to industrial application.

1. Introduction

Tomographic PIV (Elsinga et al. 2006) has attracted much attention during the last years. A considerable development of the evaluation algorithms not only resulted in an improved reconstruction quality but also in an increased evaluation speed. Applications have been demonstrated in water flows as well as in air flows with short imaging distances (Schröder et al. 2008, Novara & Scarano 2011). Longer imaging distances are restricted to low spatial resolution applications (Kühn et al. 2011). In conclusion, tomo-PIV in contrast to stereo PIV still remains far from being a standard measurement tool for industrial wind tunnel campaigns. The main problems in such environments result from the large imaging distances in combination with vibrations transferred to the imaging equipment, which spoil sub-pixel accurate calibration and thus renders a sound volume reconstruction impossible. In addition, the illumination of the volume tends to be critical. Since tracer particles for air flows are required to have maximum diameters around 1 µm, the scattered light intensity is low - especially when using high speed laser illumination.

2. Setup

The measurements have been performed at the acoustic wind tunnel Braunschweig (AWB). The AWB is an open-jet closed-loop wind tunnel with a rectangular 0.8 m by 1.2 m nozzle exit and anechoic acoustic environment. An F16 profile (chord 300 mm, span 800 mm) in high-lift configuration (Ciobaca et al. 2009) is mounted between two side plates in the test section at an angle of attack of 17°. Its flap is painted with shiny finished black paint to suppress diffuse reflections from the incident laser light. The wind tunnel flow is seeded with DEHS droplets of small diameter (~ 1 µm) and tripped to turbulent boundary layer flow on the upper surface of the flap in the gap right below the trailing edge of the main wing. A dual-cavity LEE LDP 200 MQG high speed laser operated at 3 kHz with a pulse energy of 2 * 11 mJ is used to illuminate an area of 150 mm (stream wise) * 50 mm (normal to flap surface) above the suction side of the flap. Since - due to the high repetition rate - the pulse energy is significantly lower than in a low repetition rate system, the volume was limited to a thickness of 6 mm (chord wise). In this type of setup (‘fat light sheet’), the volume information is used to gain the complete time-resolved 3-dimensional velocity gradient tensor. Two Photron APX-RS and two
Photron SA-1 cameras equipped with Zeiss Contax 180/2.8 lenses record the measurement volume in forward scattering direction from below the test section at a distance of 1.5 m. Care was taken to construct the camera support from X95 profiles as rigid as possible to reduce vibrations of the imaging system. Also, the cameras have been located outside the shear layers of the strong downwash. All cameras are arranged in one plane tangential to the model surface to prevent image background illumination by the model (dual-stereo-setup). A sequencer synchronizes the measurement system at a repetition rate of 3000 Hz with 6000 camera frames per second in frame-straddling mode, allowing pulse separations down to 5 µs. The complete imaging setup is depicted in Figure 1.

![Figure 1](image_url)

**Figure 1:** Setup overview (left) with cameras outside the shear layer below wind tunnel nozzle and laser head in the background. Magnified view of the model (right) with light sheet and calibration target in light sheet position.

3. Results

This feasibility study was designed to determine the setup parameters for future applications of tomo-PIV in industrial-scale wind tunnels. In typical measurement campaigns the lateral field of view is given by the specific application while the imaging distance is limited by the optical access to the test section. Tracer particle diameters are limited to micrometer size since they have to follow the air flow reliably. Thus, at an illumination energy limited by the available laser, sufficient image intensity can only be achieved by varying the light sheet thickness, the observation geometry and the aperture of the camera lenses used.

Here, forward scattering direction was used to optimize the imaging geometry. The largest possible aperture of the camera lenses maximizes the image intensity while minimizing the depth of focus. However, since the high-speed cameras used here have pixel sizes of 17 µm and 20 µm, the depth of focus is limited by this pixel size and not by diffraction. This leads to a depth of focus around 6 mm at the given setup and F/2.8. It turned out, that a satisfying image illumination was achieved
at the same light sheet thickness. To maintain a high quality evaluation, an increased light sheet thickness combined with the necessary smaller aperture was not acceptable.

As the chosen arrangement with pairs of cameras close to each other is non-standard for tomo-PIV, the influence of particle density on the reconstruction quality was investigated. Recordings were taken at different particle image densities (Figure 2) and evaluated with the same parameters for tomographic reconstruction and volume correlation. High-quality particle field reconstructions were possible almost to the maximum particle density investigated. Thus, the final recordings were taken at particle densities around 0.045 particles per pixel.

![Figure 2: Various seeding densities under test: 0 (left) up to 0.055 (right) particles per pixel.](image)

To compensate lens aberrations as well as imperfect focusing, a variable optical transfer function (OTF) was taken into account in the evaluation (Schanz et al. 2012). At a low seeding density, the spatial distribution of the OTF within sub-volumes was determined (compare Figure 3). From this, the space-dependent weighting function for the algebraic reconstruction of the particle field was established.

![Figure 3: Example space-dependent optical transfer function (OTF) of one camera. The volume is divided into 5 * 3 * 3 sub-volumes in x-, y- and z- direction, respectively. Depicted are the OTFs for sub-volumes around two z-planes. Note the OTF diameter rising from left to right for z = -2 mm (left image) and from right to left for z = 2 mm (right image) due to imperfect Scheimpflug-alignment. Visible pixel-like structures are display-artefacts of OTF sampling.](image)

With the optimized setup, recordings have been taken at a free stream velocity of $v_\infty = 40$, 50 and 60 m/s. Particle volume reconstruction was done with a simultaneous multiplicative reconstruction technique (SMART) based evaluation software by DLR. DaVis 8.0 by LaVision was used for the cross-correlation analysis with volume deformation. A final correlation volume size of 28 * 28 * 28 pixels was applied at an overlap of 75%. This corresponds to a correlation cube side length of 3.3 mm and a vector spacing of 0.8 mm. Contour plots of the time-averaged velocity and the corresponding RMS values are depicted in Figure 4 and Figure 5, respectively. Clearly visible is the high-momentum gap flow dividing the flow into two distinct separation bubbles (Figure 4, blue). These bubbles show a strongly intermittent behaviour as can be seen in the RMS values (Figure 5, red) and in the selected instantaneous velocity vector fields depicted in Figure 6.

![Figure 4: Contour plots of the time-averaged velocity (left) and the corresponding RMS values (right).](image)
Figure 4: Average velocity within one x-y-plane at free stream velocity $v_\infty = 40$ m/s (left) and $v_\infty = 60$ m/s (right). Colour scale adapted proportional to $v_\infty$.

Figure 5: RMS of the velocity within one x-y-plane at free stream velocity $v_\infty = 40$ m/s (left) and $v_\infty = 60$ m/s (right). Colour scale adapted proportional to $v_\infty$. 
4. Summary

Time resolved tomographic PIV measurements have successfully been performed in an industrial-grade wind tunnel at flow velocities of \( v_\infty = 40, 50 \) and 60 m/s. Transient features of the flow on the suction side of a high-lift configuration are captured in local 3-dimensional resolution (‘fat light sheet’) at a rate of 3000 vector volumes per second. Parameter studies regarding seeding density, light sheet thickness and F-number have been conducted. The promising results of the present study show a road towards the application of tomo-PIV in large scale industrial wind tunnels, aiming to finally establish this technique as a validated standard tool for wind tunnel measurements. The gained time-resolved volume data gives valuable information for the validation of prior (Ciobaca et al. 2009) and future CFD calculations.

References