Active Flow Control Investigations on a Flat Plate using PIV, Stereo-PIV and Astigmatism-PTV

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Abstract This paper evolved from results of the active flow control research at the Institute of Fluid Mechanics and Aerodynamics at the Universität der Bundeswehr München. The project generally investigates the influence of pneumatic vortex generators in flows within a Mach number range of \( M_\infty = 0.3÷0.75 \). Here, a focus on flow conditions of a single jet is set. Additionally, the applicability of Standard-PIV, Stereo-PIV and Astigmatism-PTV on the occurring high velocities and velocity gradients within turbulent flow of an under-expended jet is compared. The aim is to get knowledge of the flow characteristics and its resolvability. A commercial software was used for the analysis of the Standard-PIV and Stereo-PIV measurement data, whereas the algorithm for the Astigmatism-PTV evaluation is developed at the Institute. The well-known flow of a jet is qualified to verify the Astigmatism-PTV technique for macroscopic flow analysis. The second part of this paper presents wind tunnel results of jet flow under high subsonic flow conditions. The blowing height is shown as a function of varying \( M_\infty \), velocity ratio \( w_{jet}/u_\infty \) and Reynolds number \( Re \) set by the total pressure of the test facility \( p_t \). The results illustrate a significant blowing height dependency on \( w_{jet}/u_\infty \), whereas a changing \( M_\infty \) at constant \( w_{jet}/u_\infty = 1 \) has less influence. No significant effects of Reynolds number were detected in the measurements.

1. Introduction

A flat plate model with pneumatic jet actuators was investigated in the Trisonic Windtunnel Munich (TWM) within the framework of flow control activities at the Institute of Fluid Mechanics and Aerodynamics at Universität der Bundeswehr München. Several projects at the institute deal with applications for flow control, jet engine inlet flow (DFG FOR 1066), after body flow on rockets (DFG TRR 40) and flow control on shock boundary layer interactions. Different vortices in the actuator wake were made visible with oil flow visualization and detected by using Standard-PIV techniques in multiple planes. This kind of scanning technique causes large operating expenses in regard to campaign time and wind tunnel runs. Different possibilities of three dimensional flow field investigations were analyzed in regard to resolution, accuracy, applicability and robustness, under the background of limited optical access and dominating main flow velocity \((u, v, w)\).

In this paper the comparison of 2C2D-PIV (Standard-PIV) in multiple planes, Stereo-PIV in multiple planes and Astigmatism Particle Tracking Velocimetry (APTV) is shown. The test object is the wind tunnel model shown in Figure 1, equipped with a one slotted actuator plate blowing into the free atmosphere. Difficulties for the measurements are

- high velocity gradients at the boundaries of the jet,
- regions of interacting shock and expansion waves in case of critical jet exit conditions and
- a volume of interest of approximately \( 12 \times 15 \times 4 \, \text{mm}^3 \).

Furthermore, measurement results regarding jet blowing height of the measurement campaign in the TWM are presented. These investigations were performed by using Standard-PIV.
2. Test Setup

2.1 Jet Investigations

The measurements were performed on the fully equipped wind tunnel model (see Figure 1) with a one slotted actuator plate and a subsonic leading edge. The slot with dimensions of $10 \times 0.3 \text{ mm}^2$ (length $\times$ width) is supplied by an underlying chamber which ensures a homogeneous jet. There are connections for air supply, a pressure transducer and a temperature sensor on both sides of the model. A pressure regulator system is able to provide a maximum chamber total pressure of $p_{ch,\text{max}} = 6 \text{ bar}$ with an accuracy of $\Delta p_{ch} = \pm 5 \text{ mbar}$. The system is controlled by a LabView based user interface. The range of chamber total pressure chosen for the measurements is $p_{ch} = [1200, 2000, 3000, 4500] \text{ mbar}$. The incoming air was seeded via a Palas AFG 10.0D particle generator. A Litron Nano L200-15 PIV Nd:YAG double-pulse laser with $2 \times 200 \text{ mJ}$ was used as light source for all applications. The light sheet setups of the provided PIV/PTV-configurations are shown in Figure 2.

For Standard-PIV measurements (Figure 2a) the light sheet (thickness $0.3 \text{ mm}$) was orientated perpendicular to the surface. To get three dimensional information of the velocity field of the jet, a main plane along the slot and three additional planes normal to the first one were arranged successively. More details of the plane positions can be found in Table 1. The coordinate system is shown in Figure 7. A PCO 4000 16-bit CCD-Camera, combined with a Zeiss Macro-Planar objective ($f = 100 \text{ mm}$) was mounted perpendicular to the light sheet providing a field of view of $30 \times 19 \text{ mm}^2$ (height $\times$ width).

<table>
<thead>
<tr>
<th>Plane</th>
<th>Position [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard-PIV</td>
<td></td>
</tr>
<tr>
<td>$xz$</td>
<td>$y = 0$</td>
</tr>
<tr>
<td>$yz$</td>
<td>$x = 0$</td>
</tr>
<tr>
<td></td>
<td>$x = 2.5$</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Stereo-PIV</td>
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</tr>
<tr>
<td>$xy$</td>
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<td></td>
<td>$z = 5$</td>
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</tr>
<tr>
<td></td>
<td>$z = 20$</td>
</tr>
<tr>
<td></td>
<td>$z = 25$</td>
</tr>
</tbody>
</table>

Table 1: Regions of interest of Standard-PIV/SPIV procedures

![Figure 1: Sketch of wind tunnel model](image)

![Figure 2: Test setup for different measurement techniques](image)
The Stereo-PIV measurements were performed in planes parallel to the surface (Figures 2b and 3). The primary reason for this arrangement is to determine the maximum velocity perpendicular to the plane resolvable with this test equipment. The light sheet with a thickness of about 2mm covered the complete jet flow cross section. The height of the light sheet above the surface was varied according to Table 1. Two PCO 4000 cameras were used as recording devices. The distortion of the measurement plane was mainly corrected by the use of Scheimpflug adapters. The angle between the two optical axes was arranged at nearly 90°.

For APTV measurements, the light sheet was orientated perpendicular to the surface with a thickness of about 15 mm (Figure 2c). Due to the low intensity of the particle images the laser was reflected via a mirror. Additionally, the camera was aligned with an angle of 30° to the light sheet in order to increase the intensity by using the effect of forward scattering. Image recording was performed with the more sensitive PCO Imager sCMOS 16-bit camera and a Zeiss Macro-Planar objective lens (f = 100 mm). A cylindrical lens with a focal length of f =100 mm was implemented between objective and sensor for APTV. The achieved measurement volume has a size of 12 × 15 × 3 mm³ (length × height × depth). The actuator slot length axis was aligned perpendicular to the optical axis.

2.2 Wind Tunnel Investigations

The active flow control measurements were performed at the TWM. Figure 4 shows the test setup. A detailed description of the TWM can be found in [7]. The model is equipped with a 1-slotted actuator plate with the center of the slot at x = 220 mm behind the leading edge. The skew angle between the slot length axis and the main flow direction was chosen to be 30°. Due to the run time of the wind tunnel, Highspeed-PIV in the standard (2C2D) configuration was used. The light sheet was orientated in the main flow direction normal to the surface and was provided by a Quantronix Darwin-Duo Nd:YLF double pulse laser. Recording was performed with two Phantom v12 CMOS cameras with Zeiss 180 mm objectives and software package LaVision Davis 7.2. To increase the spatial resolution near the jet exit an additional collecting lens (f = 600 mm) was integrated. A strip of nonskid tape with aluminum oxide abrasive grid from FIXUM (thickness 1 mm, width 19 mm), situated at the end of the nose curvature, was used in order to generate a fully turbulent and also thicker boundary layer. The measurement conditions are shown in Table 2.
<table>
<thead>
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<th>$Re$ [m$^{-1}$]</th>
<th>Wind tunnel total pressure $p_t$ [bar]</th>
</tr>
</thead>
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<td>$P_{stat}$ [mbar]</td>
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<tr>
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<td>$1.30 \times 10^2$</td>
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<tr>
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<td>$2.03 \times 10^7$</td>
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<tr>
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<tr>
<td>0.75</td>
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<td></td>
<td>1377</td>
</tr>
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</table>

Table 2: Reynolds numbers as a function of Mach number and total pressure

3. Measurement and Analysis

3.1 Jet Investigations

For Standard-PIV measurements, the light sheet and the camera were adjusted and the model was placed according to the setup conditions in Table 1. A 2D calibration target (dots, diameter 2mm, distance 10mm) was used for spatial calibration. The time between two laser pulses was chosen according to the maximum velocity (which is a function of $p_{ch}$) to get a particle image shift of approximately 10 pixel in regions of maximum velocity. In every test case, 400 double images were taken. Data evaluation was done first with Davis 8.0, with an averaging over 400 vector fields obtained from multi-pass cross-correlation and decreasing window size to $12 \times 12$ pixel with 50 % overlap in the $xz$-planes and $8 \times 8$ pixel with 50 % overlap in the $yz$-planes. Due to the mentioned regions of shock characteristics at higher chamber pressures, a second data processing was performed using a single pixel ensemble correlation method (see [3, 6, 8]) to increase the spatial resolution.

Stereo-PIV measurements followed a similar procedure as the one described for Standard-PIV. The light sheet and the cameras with Scheimpflug adapters were arranged as mentioned in Section 2. Both views were calibrated with a three dimensional dual plane target (dots, diameter 1 mm, distance 10 mm, plane distance 2 mm). The different test setups were realized by adjusting the height of the model with respect to the field of view. The data was evaluated in Davis 8.0 with Stereo-PIV cross-correlation. The averaged velocity field was calculated from 300 double images per camera, per test case and measurement plane. The Stereo-PIV self-calibration function was used to improve the calibration precision and processing stability. The correlation window size was adapted in relation to the region of interest and particle density. A size of $12 \times 12$ pixel with 50 % overlap was used in all planes.

The basic principle of APTV is the detection of spatial positions of particles and their tracking in two consecutive images using a single camera. Details can be found in [1, 2]. The position information in depth (here: $y$-position) is provided by the semi-axis distortion of the particle image. Two focal planes were generated in the depth direction using a cylindrical lens. Their positions can be determined by moving a calibration target along the optical axis. The calibration for all presented measurements was performed by moving a grid with millimeter spacing equidistantly in 0.5 mm steps. While the horizontal
lines are distinguished in one focal plane using an opened aperture, the vertical lines are highlighted in the other focal plane under the same conditions. A statistical analysis of the length of both semi-axis of all particle images recorded leads to a respective minimum semi-axis size connected to the corresponding focus. The remaining x- and z-positions can be calculated as a function of the y-position and image coordinates. Therefore, the grid has to be moved along the optical axis with a closed aperture to ensure a maximum depth of focus. This leads to a calibration function which transfers the image coordinates to their 3D positions. Data recording was done by using Davis 8.0. A single set of 1000 double images per test case was recorded. APTV data evaluation was performed using an algorithm designed at the institute (see [1, 2]). An essential requirement to ensure suitable results using this algorithm is the accurate determination of the semi-axis of a particle image. This objective can be achieved by adjusting the seeding density to avoid overlapping particle images. Figure 5 illustrates a typical Standard-PIV (Figure 5a) and an APTV image (Figure 5b) on a corresponding case of jet flow at \( p_{ch} = 1200 \) mbar, where in the latter case seeding density is much lower. The optimum particle image diameter for Standard-PIV in this case is about 2-3 pixels [5]. In contrast, APTV requires a particle diameter of at least 5 pixels to determine the semi-axis with sufficient accuracy.

4. Results

4.1 Jet Velocity

The maximum jet velocity \( w_{jet} \) can be calculated according to Equation 1 (for air \( \kappa = 1.4 \) and \( R = 287 \) J/(kgK)). The static pressure during the measurements was \( p_{stat} = 955 \) mbar and the chamber temperature was nearly \( T_{ch} = 295 \) K.

\[
w_{jet} = \sqrt{\frac{2\kappa}{\kappa-1} RT_{ch} \left[ 1 - \left( \frac{p_{stat}}{p_{ch}} \right)^{\frac{\kappa-1}{\kappa}} \right]}
\]

(1)

The comparison between theoretical velocity and measured results is shown in Figure 6. The Standard-PIV velocity is calculated from the vectors in the xz-plane of the Standard-PIV measurements. The agreement between theory and actual data for the maximum velocities shows that the

![Figure 6: Theoretical and PIV measured jet velocity as a function of chamber pressure](chart.png)
entire velocity range (0-480 m/s) is resolvable with this technique. Furthermore, the Standard-PIV results can serve as reference for all other recording techniques. The error bars show the deviation of the measured jet velocity. The velocity RMS value of $w_{rms} = 50$ m/s results from the high intensity of turbulence in the jet flow.

In Figure 7, the 3D results of the different measurement techniques showing jet flow at a chamber pressure of $p_{ch} = 2000$ mbar are visualized. In Figure 7a and 7b color coded is the average velocity $\bar{w}$. Figure 7c shows detected vectors colored with their instantaneous velocity $w$. The jet air the velocity information is only available within the jet’s boundary because of seeding particles only inside. The non-seeded parts of the planes are blanked for visualization purposes. For reasons of comparability, the results are displayed only up to $z = 15$ mm.

![3D visualization of jet velocity](image)

**Figure 7**: 3D visualization of jet velocity $w$ at $p_{ch} = 2000$ mbar

Figure 7a presents the four 2C2D-planes of Standard-PIV. Only some of the in-plane vectors are displayed for the visualization. The velocity field of the $xz$-plane shows a good span-wise homogeneity at the jet exit as well as symmetry with the $yz$-plane. Vectors from the $yz$-plane indicate a small tilt between the main jet direction and the $z$-axis with an angle of approximately $\delta = 2^\circ$. The velocities at the edges of the different planes are in good agreement with each other, which leads to two conclusions. First, the jet conditions can be repeatably arranged without problems and secondly, the light
sheet of the \(xz\)-plane is thin enough to exclude the influence of the gradient at the jet boundary near the exit. The results of Stereo-PIV (Figure 7b) match the velocities of Standard-PIV. Even \( \overline{\omega} \) can be resolved in the plane at \( z = 3 \) mm due to the self-calibration function. The jet expands in \( y\)-direction with increasing distance and gets more elliptical. Investigations with Stereo-PIV in horizontal planes of a jet flow were also made by [4]. The change of primary- and secondary-axis reported in [4] cannot be confirmed. The described phenomena appears in [4] at a height of about \( z = 70 \) mm. The measurements of this project were performed at a maximum height of \( z = 25 \) mm. APTV (Figure 7c) provides results of \( \omega\)-Velocity in the same magnitude. The spatial resolution is less than the resolution of Standard-PIV because of the number of images taken and the detected particle image pairs. The distribution of the presented data is scattered. In the region of \( x = 5 \) mm and \( z = 0 \) mm, no vectors can be found. This is caused primarily by an overlapping gap of the two laser pulses and results in areas of low intensity in the second frame.

Standard-PIV reflects the velocity gradient of \( \overline{\omega} \) with high accuracy, but it is not possible to analyze the jet topology. Therefore, Stereo-PIV is necessary. The expanding jet and its topology is well described by measure several horizontal planes. APTV allows for the acquisition of the complete information at a single technique with a high resolution.

![Graphs showing average jet velocity comparison](image)

**Figure 8:** Comparison of average jet velocity \( \overline{\omega} \) of different measurement techniques
The calculated average velocity $\overline{w}$ as a function of $z$ is presented in Figure 8 for different chamber pressures $p_{ch}$. The black lines show the results of Standard-PIV measurements in the $xz$-planes. Every fourth data point is marked with a cross. The blue triangles represent the discrete velocities calculated from the Stereo-PIV results. The red line with squares is the outcome of APTV. Every second data point is marked. The error bars represent the RMS of the average main velocity component $w_{rms}$.

A good consistency in the average velocity $\overline{w}$ and in the RMS $w_{rms}$ determined by the different measurement techniques can be seen at every chamber pressure. The basic characteristics of the jet, maximum velocity and slope, are in a limit of $\Delta \overline{w} = \pm 5\%$ except for a few outliers equal to each other. Basically, velocities up to 480 m/s can be resolved in plane with Standard-PIV. Also in plane-perpendicular with Stereo-PIV and three dimensional with APTV. However, Figure 8d shows a limit of Stereo-PIV and APTV methods in the presented measurements. At $z = 0 \pm 3$ mm three discrete maxima are present in the Standard-PIV results, which cannot be detected by the other techniques. These peaks are caused by shock and expansion phenomena due to an under-expanded jet. Besides, the RMS $w_{rms}$ of the different measurement techniques varies. The huge fluctuation in the APTV’s $w_{rms}$ results from the tracked, instantaneous velocity vectors, whereas the velocity plots of both PIV methods are calculated from the average of 400 instantaneous velocity fields. Hence the related RMS $w_{rms}$ of APTV has a greater fluctuation. However, the APTV displays the shape and velocity gradient very well. The increasing $w_{rms}$ of Standard-PIV at $z = 17 \pm 22$ mm in Figure 8a, b and 8c results from some lasting spurious vectors due to poor seeding density.

Figure 9 shows details of the Standard-PIV data at $p_{ch} = 4500$ mbar. The top of Figure 9a illustrates the normalized average velocity $\overline{w}/\overline{w}_{max}$. In the bottom part of the figure the normalized average image intensity $\overline{T}/\overline{T}_{max}$ is depicted. Regions of local velocity maxima are followed by a high normalized average intensity. Figure 9b shows the spanwise average of both parameters over $z$. The $\overline{T}/\overline{T}_{max}$-axis is logarithmically scaled for visualization purposes.

Figure 9: Comparison of velocity and intensity at $p_{ch} = 4500$ mbar
The accumulation of particle images (high normalized intensity) after an intense decrease of velocity is clearly visible. This indicates the existence of shock-waves occurring in under-expanded jets. The increasing fluid density after the shock waves causes an increase of particle density. Standard-PIV is able to resolve the shocks with a distance of less than a millimeter to each other. Figure 9 confirms the shape of the velocity profile from Figure 8d and verifies the conclusions mentioned above.

4.1 Wind Tunnel

Investigations at TWM concern the performance of the pneumatic vortex generators. The results dealing with jet blowing height are presented in regard to jet characteristics. To prevent an inherent increase of drag, it is necessary to keep the vortex generation inside the boundary layer. This assumes the knowledge of dependencies according to chamber pressure \( p_{ch} \), Mach number \( M_\infty \) and Reynolds number \( Re \). In this test facility the Reynolds number strongly depends on wind tunnel total pressure \( p_t \) and can be varied independently of the Mach number. In order to measure the blowing height only the air supply of the actuator was seeded. Figure 10 shows exemplarily the result of the measured jet at \( p_{ch} = 2000 \text{ mbar}, \ M_\infty = 0.3 \) and \( p_t = 2000 \text{ mbar} \). The mean intensity \( \bar{T} \) is plotted as contour and clearly displays the boundary of the jet (red line). An investigation of the relation between blowing height and \( p_{ch} \), \( M_\infty \) and \( p_t \) is presented in Figure 11. As expected, Figure 11a shows a significant dependency of height on \( p_{ch} \) at constant \( M_\infty \) and \( p_t \). By doubling the chamber pressure, the jet has more than twice the height. In this case the varying chamber pressure means a change in the velocity ratio \( w_{jet} / u_\infty \). Less influence on the blowing height can be detected when \( M_\infty \) is varied, this indicates that the velocity ratio is kept constant as \( w_{jet} / u_\infty = 1 \) (Figure 11b). The Reynolds number effect of the free flow, influenced by varying the total pressure \( p_t \) of the wind tunnel facility, shown in Figure 11c, has no significant effect on the height.

![Figure 10: Mean Intensity \( \bar{T} \) of seeded actuator slot at \( p_{ch} = 2000 \text{ mbar}, \ M_\infty = 0.3 \) and \( p_t = 2000 \text{ mbar} \)](image1)

(a) Blowing height as function of \( p_{ch} \) at \( M_\infty = 0.3 \) and \( p_t = 2000 \text{ mbar} \)

![Figure 11: Results of blowing height investigation](image2)

(b) Blowing height as function of \( M_\infty \) at and \( p_t = 2000 \text{ mbar} \)

(c) Blowing height as function of \( p_t \) at \( M_\infty = 0.3 \) and \( p_{ch} = p_t \)
5. Conclusion

The first part illustrates the following results for the different measurement techniques:
Standard-PIV shows good resolvability of high velocity gradients even on shock waves which closely follow each other. APTV is a technique which enables the measurement of a three dimensional flow field with only one attempt in contrast to Standard- and Stereo-PIV. To detect the shock waves the vector density was not high enough. This measurement technique enables future flow control investigations to get three dimensional flow field information.

The measurement analysis of the TWM investigation provided information concerning the blowing height relations. As expected, it was shown that the height significantly depends on the velocity ratio \( w_{jet} / u_{\infty} \). The Reynolds and Mach number effects on the blowing height are negligible.

6. Acknowledgement

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References


