PIV investigation of a planar supersonic wake flow

by

F. Scarano(1) and B. W. van Oudheusden(2)

Delft University of Technology,
Faculty of Aerospace Engineering – Aerodynamics
Kluyverweg 1, 2629 HS, Delft, The Netherlands

(1) E-mail: f.scarano@lr.tudelft.nl
(2) E-mail: B.W.vanOudheusden@lr.tudelft.nl

ABSTRACT

The study describes the application of particle image velocimetry (PIV) to anisotropy investigate the compressible flow in the wake of a two-dimensional blunt base. Experiments are performed in a supersonic blow-down wind-tunnel at $M_\infty = 2.01$. Specific issues related to the application of PIV to supersonic flows are discussed, such as the seeding particle flow tracing fidelity and the measurement spatial resolution. The seeding particles response time through a planar oblique shock wave is assessed with PIV. The measurement spatial resolution is enhanced by adopting an advanced cross-correlation algorithm to interrogate the particle image recordings with iterative window deformation and multi-grid adaptive resolution. The measurement yields the spatial distribution of mean and turbulent velocity. The measurement accuracy is assessed comparing the measurement with compressible flow theory across the expansion fan around the base edge. The mean velocity distribution clearly reveals the main flow features such as expansion fans separated shear layers, flow recirculation, reattachment, recompression and wake development. The turbulence distribution shows the growth of turbulent fluctuations in the separated shear layers up to the reattachment location. Weak velocity fluctuations are also present downstream reattachment outside of the wake due to unsteady flow reattachment and recompression. The instantaneous velocity field is analyzed seeking for coherent flow structures in the redeveloping wake. The instantaneous planar velocity and vorticity measurement returns evidence of large-scale turbulent structures detected as coherent vorticity fluctuations. The velocity pattern shows large masses of fluid in vortical motion consistently. The overall instantaneous wake flow is considerably organized as a double row of counter-rotating structures. The single structures show vorticity contours of roughly elliptical shape in agreement with previous studies based on spatial correlation of planar light scattering. Peak vorticity is found to be five times higher than the mean vorticity value, suggesting that wake turbulence is dominated by the activity of large-scale structures.
1. INTRODUCTION

The supersonic separated flow behind a two-dimensional base is characterized by a complex interaction of expansion waves with the free shear layers and compression waves. The shear layers delimit a separated region that develops into the object wake downstream. The problem relevance is given by high-speed applications of projectiles and powered missiles where it is desirable to improve the aerodynamic performance, in particular reducing the drag coefficient. Fig. 1 depicts the flow features of a compressible base flow by means of velocity magnitude color-contours and a set of stream-traces as obtained from the actual planar velocity measurements. The separation point is located at the base corner, given the sharp base edge. The flow expands from the separation point at the shoulder of the base, following a Prandtl-Meyer expansion fan. Two free shear layers delimit the separated flow region where the flow recirculates at subsonic speed. At the reattachment location the flow undergoes a gradual compression and the two shear layers merge to form the redeveloping wake. The challenging aspects of the flow problem are given by the intense velocity and density gradients across the free shear layer, which dominate the near-wake region. The fluid - dynamics is made even more complex by the flow turbulence that develops along the shear layers where large-scale coherent structures play a dominant role in the process of turbulent diffusion.

Several investigations over the last decade (Amatucci et al., 1992; Herrin and Dutton 1994-97, Lachney and Clemens, 1998) have been devoted developing experimental insights in order to understand the complex behavior of the turbulent compressible flow separation past blunt based objects. The mean flow topology, turbulence statistics and large-scale turbulent structures have been extensively covered by experimental studies on both planar (Smith and Dutton, 1996; Lachney and Clemens, 1998) and axisymmetric geometries (Herrin and Dutton, 1994; Bourdon and Dutton, 1999). Laser Doppler velocimetry (LDV) has been demonstrated to be the most adequate diagnostic technique to describe the flow turbulence, being non-intrusive and capable of resolving the sharp velocity profile across the thin free shear layers (measurement volume cross section of the order of 100 µm) and in the redeveloping wake (Herrin and Dutton, 1995). However LDV, as a point-wise measurement technique, is not suitable to directly investigate large-scale flow structures. The spatial coherence of unsteady velocity fluctuations cannot be described with a point-wise measurement approach unless specific assumptions can be made on the nature of the fluctuations so as to allow phase reconstruction. Therefore, multi-point or better whole-field measurement techniques must be employed in order to access and understand the spatial flow organization and further to quantify the degree of coherence of the velocity-vorticity fluctuations.

Planar laser techniques have been utilized to visualize coherent structures in compressible mixing layers. Extensive investigations using Mie scattering and PLIF have been conducted by Clemens and Mungal (1991, 1995) and by Samimy et al. (1992). The structure of reattaching shear layers separating from blunt-based objects at supersonic speeds has been thoroughly investigated by Smith and Dutton (1996) and Bourdon and Dutton (1999). Side views and end views of the light scattering pattern have been reported with evidence of large-scale structures along the shear layers and at the wake interface. Their results described the size, eccentricity and orientation of the coherent structures by means of statistical analysis (spatial correlation) of large ensembles of images. Smith and Dutton (1999) addressed the advection velocity of turbulent structures and also proposed a systematic method to analyze large ensembles of images obtained from a double-pulsed illumination-recording system similar to that used for PIV. Although the planar visualization technique demonstrated to be successful in the visualization of turbulent structures, several flow features are still missing due to the inability of the technique to directly measure the flow instantaneous velocity. Therefore, the natural extension of planar visualization techniques is seen in those methods that are capable of yielding instantaneous quantitative planar flow measurements such as PIV and Doppler global velocimetry (DGV). Samimy and Wernet (2000) reviewed the state-of-the-art of both techniques for high-speed applications concluding that the DGV technique has been under development for relatively short and is only now emerging as a powerful technique in high-speed flows (Arnette et al. 1998). Conversely, PIV is a well-established technique in low-speed and is gaining confidence in high-speed experiments.

The application of PIV in compressible flows was pioneered by Kompenhaus and Höcker (1988) who used photographic recording and an image-shifting technique. It has developed into a more accessible technique with the advent of frame straddling CCD cameras and short-duration nanosecond-pulsed double cavity Nd:Yag lasers. Investigations range from supersonic jets (Krothapalli et al., 1994; Lourenco, 1996-1999) to transonic turbo-machinery flows (Raffel et al., 1998; Wernet, 1998). Turbulence measurements in compressible mixing layers have been recently performed with PIV by Urban and Mungal (2001). Instantaneous snapshots of planar velocity and vorticity were obtained at several values of the convective Mach number $M_c$, obtaining planar maps of turbulence statistics from ensemble averages. The present investigation focuses on the assessment of the PIV technique as a complementary approach to the study of compressible wake flows in a relatively large-scale supersonic facility. The first part of the discussion describes PIV related problems such as particle dynamic response and spatial resolution. An innovative image processing method is shortly described that allows improving the measurement spatial resolution, which is considered a crucial aspect in such a flow configuration where a wide range of spatial scales occurs. In the second part the results of the measurement in the wake of a two-dimensional base are presented along with the assessment of the experimental uncertainty of mean and turbulent flow quantities. Finally the attention is focused on the large scale flow
structures appearing in the redeveloping compressible wake. Planar snapshots show the structure and topology of instantaneous velocity and vorticity fluctuations.

2. EXPERIMENTAL APPARATUS and PROCEDURE

Flow facility and model

The present experimental investigation is performed in the transonic-supersonic wind-tunnel (TST) of the High-Speed Aerodynamics Laboratories at Delft University of Technology. The facility is a blow-down type wind tunnel that can generate flows in a Mach range from 0.5 to 4.2 in the test section. The test section area is 300 \((W) \times 270 \,(H) \text{ mm}^2\) and the tunnel operates at values of the unit Reynolds number ranging from \(38 \times 10^6\) to \(130 \times 10^6 \text{ m}^{-1}\). In the transonic and supersonic range, the Mach number is set by means of a continuous variation of the throat section and flexible upper and lower nozzle walls. Dry and oil-free compressed air is provided by a 6.1 MW compressor plant, and stored at 40 bars in a 300 \(\text{m}^3\) volume storage vessel. The 14500 kg of stored dry air is sufficient for the blow-down use of the wind-tunnel for 300 s. The two-dimensional model producing the base flow consists of a symmetrical double wedge with sharp leading edge imposing a flow deflection of 11.31°, followed by a thick plate 50 mm long and of constant thickness \(h = 20\) mm. The plate terminates sharply with a vertical base. The model spans the entire section width. The investigated flow region includes the whole separated region behind the base as well as the shear layers and the redeveloping wake. The flow around the model is optically accessible in order to be able to assess the upstream flow conditions as well. In the present experiments the wind-tunnel is operated at a stagnation pressure of 200 kPa and the nozzle throat is set so as to obtain a free-stream Mach number \(M_b = 2.01\). The Mach number over the thick plate is then \(M_e = 1.99\) as predicted from shock-expansion theory and confirmed by the PIV measurements. The color Schlieren photograph in Fig. 2 illustrates the flow around the wedge-plate model. The density gradient is visualized in red, green and blue for vertical lower, vertical upper and horizontal light beam deflection. A planar oblique shock wave (OSW) is created at the model nose followed by a Prandtl-Meyer expansion fan at the first shoulder. A second expansion occurs when the flow separates at the model base. The free shear layers developing downstream are visualized as blue streaks. The flow re-compression around the reattachment location occurs with compression waves emanating from the concave streamlines region.

![Schlieren photograph](image)

*Fig. 2. Color Schlieren photograph of the supersonic flow around the wedge-plate model.*

Measurement technique

In the present investigation two-component PIV is implemented for the measurement of the instantaneous velocity distribution over the vertical symmetry plane \((x-y)\) of the model. Operating PIV in a supersonic wind-tunnels requires the solution of several problems. First of all seeding particles of small size must be introduced and uniformly dispersed in the flow. Secondly, the test section must be optically accessed by the laser sheet to illuminate the tracers and by the CCD camera to record their scattered light.

Seeding procedure

A fraction of the flow is seeded in the settling chamber by means of a seeding distributor bar with 6 orifices. The bar is placed vertically in the settling chamber producing a seeded stream-tube of flow of approximately \(6 \,(H) \times 3 \,(W) \text{ cm}^2\) in the test section. Under operating conditions, the seeded flow exhibits a mean particle concentration of about 10 particles/mm\(^2\), as estimated from the single exposure PIV recordings. The interference of the seeding device with the flow is assessed by performing Hot Wire Anemometry (HWA) measurements of the free stream flow along vertical and horizontal profiles in a cross section of the flow at the measurement location. No difference is revealed in the mean flow
distribution with and without the seeding device. The free stream turbulence intensity shows an overall increase of about 0.2% introducing the seeding device, which is considered acceptable for the present investigation. No evidence of non-homogeneous turbulence is revealed by the HWA measurements apart from the tunnel side-wall boundary layer. The particle-laden flow is produced by entraining Titanium dioxide (TiO₂) particles with a high-pressure cyclone separator operated at 10 bars. The nominal particle median diameter is $d_p = 0.27 \, \mu m$, with a specific gravity of $\rho_p = 4.0 \times 10^3 \, kg/m^3$. However the effective size of particle tracers varies considerably with the operating conditions due to incomplete particle separation in the entrainment phase. Moreover, also the effective density of the seeds is not directly determined by the specific gravity of the material and the bulk density may be considerably lower due to the porous nature of the particle agglomerates. According to the technical support of the company that provides the seeding particles, a typical bulk density $\rho_b = 10^3 \, kg/m^3$ is expected in the present operating conditions (dehydrated and non-compacted powder). Urban and Mungal (2001) made similar considerations concerning the properties of the agglomerated seeding tracers in relation to the size of single particles. The conclusion seemed to be: the smaller the initial particle size, the smaller will be the final tracer particle size (with agglomeration). The above authors reported that the control of particle agglomeration to pursue mono-dispersed seeds can be obtained using several hydrodynamic based devices (fluidized bed, cyclone, impactor). Due to the problem of particle agglomeration and to the uncertainty on the effective particle density, the seeding particle properties can be predicted only with a rough approximation. However, it is possible to accurately infer the combined effect of the particle size and density from the direct measurement of the particle tracers response to a well-known forcing input. A planar oblique shock wave constitutes the commonly adopted test, which corresponds to a sharp velocity falling edge, through which particle tracers gradually decelerate due to their finite inertia. Such a procedure was adopted in previous investigations (Amatucci et al., 1992; Melling, 1997; Raffel et al., 1998; Urban and Mungal, 2001, among others) where the particle relaxation time $τ_p$ is evaluated from the measurement of the relaxation length/time and knowledge of the flow velocity behind the shock wave.

![Fig. 3. Mean velocity distribution across an oblique shock wave. Velocity vector, normal velocity component contours and stream-traces.](image)

The supersonic flow across the planar OSW created at the model nose is analyzed in the same conditions as those of the base flow experiment. The particle velocity across the OSW is measured by means of PIV. The images are interrogated at a spatial resolution of 0.57 mm/window (21 pixels) and 70% overlap factor ($OF$), yielding a data spacing of 0.17 mm. The ensemble mean from a set of 100 instantaneous velocity fields is shown in Fig. 3. The velocity vector profiles show the uniform flow upstream and downstream of the shock, which is also emphasized by the parallel stream-traces pattern. The velocity component normal to the shock wave is displayed in color contours. A velocity profile is extracted perpendicular to the shock wave to quantify the particle velocity downstream of the shock wave (particle relaxation length and time) and the result is shown in Fig. 4. The mean particle velocity before and after the shock is compared with OSW theory and the results are described in section 0.

The velocity difference across oblique shock waves can be obtained from the formulation of normal shock wave properties, provided that the normal velocity component is considered along the direction perpendicular to the shock wave. Given the values of the incoming Mach number and of the shock angle $β$, the shock wave properties are uniquely determined. The direct measurement of the velocity spatial distribution makes it possible to determine the particle velocity profile along a chosen abscissa. The velocity profile is extracted perpendicular to the SW in order to quantify the particles Eulerian relaxation length.
The measurement of the non-dimensional particle (slip) velocity \( \frac{(U_n - U_{n2})}{(U_n1 - U_{n2})} \) is plotted versus distance in Fig. 4 (bottom axis). The particle relaxation length \( \xi \) is obtained with the aid of an exponential curve fit, which returns \( \xi = 0.76 \text{ mm} \). The measurement reliability is confirmed by the very good exponential fit obtained with the present data. However, the effects the finite spatial resolution is evident mostly around the shock location \( s = 0 \). In fact at about half a window size upstream \( s = -0.28 \text{ mm} \) the measured velocity starts decreasing due to the averaging effect intrinsic to the PIV interrogation method. In order to infer the particle relaxation time \( \tau \) from the present measurements, the relation \( \tau = \frac{d}{18\mu} \left( 1 + K \frac{d}{(M/Re)} \right) \) was obtained by knowledge of the relation \( d = \frac{1}{(M/Re)} \) and \( \tau = \frac{d}{18\mu} \). The results returned the unevenly spaced data series (circles) to be referred to the upper axis. The exponential curve fit yields \( \tau = 2.4 \mu \text{s} \), which in turn gives a frequency response \( f_p = 417 \text{ kHz} \).

The above measurement can be compared with the behavior predicted from the modified Stokes drag law (spherical particles) valid for small particles. In the present case \( (d_p = 0.27 \mu\text{m}, \rho_p = 10^3 \text{ kg m}^{-3}) \), given the relatively low value of the Mach number and particle diameter based Reynolds number, the drag relation suggested by Melling (1986) yields the following expression for the relaxation time

\[
\tau_p = \frac{d_p^2 \rho_p}{18\mu} \left( 1 + 2.7Kn_p \right)
\]

(2-1)

In the present flow conditions \( (Kn_p = 1.26\sqrt{\frac{P}{M/Re}}) \) the above equation yields \( \tau_p = 1 \mu\text{s} \). The discrepancy with the result obtained from the measurement is ascribed to the effect of particle agglomeration. The fidelity of the flow tracers in turbulent flows can be quantified referring to the Stokes number \( S_k \), the ratio between \( \tau \) and the characteristic flow time scale \( \tau_f \). The most critical conditions are met downstream of separation (Herrin and Dutton, 1995) where the shear layer thickness is estimated as \( \delta = 1 \text{ mm} \). Samimy and Lele (1991) suggest the following expression for the flow time scale \( \tau_f \)

\[
\tau_f = 10\frac{\delta}{\Delta U}
\]

(2-2)

In the present experiment \( \tau = 17 \mu\text{s} (\Delta U = 580 \text{ ms}^{-1}) \) and the resulting particle Stokes number is \( S_k = 0.14 \). Following the particle dynamics computation of Samimy and Lele (1991) the associated RMS slip velocity is 2.5\%. At the reattachment location and downstream the Stokes number drops below 0.05 with an associated RMS slip velocity of 0.7\%. One may conclude that for the present experiments the error associated to the finite particle response can be neglected starting from \( x = 10 \text{ mm} \) downstream of the base. It is also concluded that the accurate measurement of the particle relaxation time with PIV is a technically challenging task due to several reasons. The most important sources of error are found to be: a) the relatively large size of PIV interrogation windows (spatial resolution); b) the time separation between laser pulses (temporal resolution); unsteady position of the shock due to free stream turbulence (ensemble averaging); optical distortion due to index of refraction effects (spatial blur). However a detailed discussion of the argument goes beyond the scope of the present paper.
Particle illumination and recording

The light source is a double-cavity pulsed Nd:Yag laser with 400 mJ pulse energy and 6 ns pulse duration at a wavelength of 532 nm. The output beam has a diameter of 7 mm and is shaped into a sheet 500 μm thick illuminating an area of about 300 (L) × 200 (H) mm². The laser pulse separation \( \Delta t \) is set to 1.0 μs yielding a reference particle displacement of about 0.5 mm in the free stream flow. The light is inserted in the flow from the bottom side of the tunnel and reflected towards the model with a prism (Fig. 5).

![Fig. 5. Schematic of light sheet delivery in the TST wind-tunnel test section.](image)

The light scattered by the particle tracers is imaged with a 60 mm focal length lens \( f_l = 5.6 \) for FOV-1, \( f_l = 11.2 \) for FOV-2 on a 12 bit, Peltier-cooled charge coupled device (CCD) digital camera with frame straddling architecture. In order to describe the free shear layer and the coherent structures in the redeveloping wake with sufficient spatial resolution, different fields of view are chosen. The measurement of the overall wake is performed with a field-of-view (FOV-1) of 64 (W) × 50 (H) mm² (50 μm/pixel), whereas the detail view (FOV-2) is 25.6 (W) × 20.5 (H) mm² (20 μm/pixel). Despite the CCD high spatial resolution of 1280 (W) × 1024 (H) pixels, the diffraction limited spot ranges from 125% to 280% of the pixels size (6.7 μm), therefore the particle images are slightly under-resolved with consequent peak-locking effect (Westerweel, 1997). The scattered light pattern relative to each time instant is stored onto separate recordings, which allows analyzing the images with cross-correlation-based algorithms. With respect to auto-correlation analysis, cross-correlation has the major advantage of resolving the directional ambiguity and to have a higher signal-to-noise ratio (S/N) of the correlation signal. As a result higher accuracy and resolution are usually obtained (Raffel et al., 1998). The acquisition rate of PIV recordings is 3.3 Hz limited by the digital communication line bandwidth of the acquisition system. Data sets up to 550 and 230 recordings are acquired for cases FOV-1 and FOV-2 respectively.

PIV image interrogation

The interrogation of the PIV recordings is performed with an advanced cross-correlation technique. The method is based on the deformation of the correlation windows with an iterative multi-grid scheme (WIDIM), which is demonstrated to significantly improve the measurement accuracy up to one order of magnitude with respect to basic cross-correlation (Scarano and Riethmuller, 2000).

The first image interrogation is performed at a coarse resolution and a displacement field is obtained, which is used to deform the PIV recordings one respect to the other (at the reference location \( r_{o} \)). The interrogation windows \( I_{o} \) and \( I_{i} \) are then selected according to the displacement predictor (at \( r_{o} - \delta r/2 \) and \( r_{o} + \delta r/2 \) respectively) in order to maximize the particle image pairs. The iterative process aims at transforming \( I_{o} \) and \( I_{i} \) into \( I_{o,2} \), which represents the particle image pattern that would be recorded at the time instant \( t + \Delta t/2 \). Since the method compensates for the in-plane particle motion including the first derivatives of the spatial velocity distribution, therefore the method is suited for the robust analysis of particle image motion with a high deformation rate, which occurs for the present flow features (shear layers, shock waves, expansion fans).

A particular implementation of the method is adopted in the present investigation in order to achieve adaptive spatial resolution (AR-WIDIM). The basic principle of the method consists of suppressing the unnecessary constraint that the interrogation window size is constant over the analyzed image. Similarly to what is obtained with solution-adaptive meshing methods in the domain of computational fluid dynamics, the measurement points are chosen with a density according to criteria based on intermediate interrogation results. In particular, the spatial data sampling density is chosen so as to follow the scale of the velocity fluctuations. A detailed discussion and assessment of the method are given in a review study about iterative PIV interrogation methods (Scarano, 2002). The images recorded in the present experiments are analyzed within a window size range of 21 to 51 pixels side and a mean window overlap of 75% is applied. In the
present study there are two reasons for adopting an overlap factor larger than the commonly adopted value of 50%. First, a higher accuracy in the iterative image deformation method is obtained. Second, reducing the grid spacing the spatial derivatives of the velocity field are evaluated with smaller truncation errors by finite differences.

Fig. 6. Principle of the image deformation interrogation method. I_{1/2} interrogation region and particle image pattern; I_a backward deformed window; I_b forward deformed window.

The measurement uncertainty related to the image interrogation method has been assessed through the measurement of the free stream turbulence intensity. The rms fluctuation of the velocity is 0.03 pixels (1.5 m/s) upstream of the expansion fans (uniform flow) and it increases up to about 0.08 pixels (4.0 m/s) inside the expansion fans regions (weak velocity gradient). The outcome is in agreement with an assessment performed with synthetic particle images (Scarano and Riemthuller, 2000). Given a time separation $\Delta t = 1 \mu s$ and the free stream velocity $V_\infty = 505$ m/s, the reference particle image displacement is $\delta r = 10$ pixels for the smallest magnification and $\delta r = 20$ pixels for the close views. The error associated to the image processing is therefore in the order of 1%. The measurement confidence level was of more difficult assessment since technical limitations of the experimental apparatus did not allow to achieve a homogeneous and constant flow seeding. Moreover, spurious light reflected from the model base degraded the velocity measurement close to the model. The confidence level is related to the probability that a given velocity vector is the result of a spurious peak in the correlation map. In the present study such a probability is associated to that false vector detection. In the most critical region close to the base (spurious light scattered from the model surface, noisy background) the result of the ensemble statistics yields a 50% confidence level. This region is therefore not shown in the measurement results. Starting from $x/h = 1.0$ the confidence level is above 80% along the shear layers and it approaches 98% outside.

3. RESULTS

The experimental results are discussed in three parts. First the mean flow around the base is presented with an assessment of the results. The structure of the mean free shear layer obtained from measurements at higher resolution is also presented. Next, the spatial distribution of the turbulence intensity is discussed, which introduces to the last part where the results deal with the unsteady turbulent nature of the flow in the redeveloping wake.

Statistical flow quantities

The mean flow topology is described in Fig. 7 (left) as obtained from ensemble-averaging 550 instantaneous velocity fields. The velocity vector profiles are under-sampled (1/6) for clarity of representation. Spurious light reflections from the base model do not allow measuring closer than 3 mm to the model base surface. A parallel and uniform stream is measured upstream of the base corner expansion. The stream-trace patterns reveal a symmetrical separated region organized with two counter-rotating regions. The center of rotation is observed at $x/h = 0.57$, and the reattachment location follows at $x/h = 1.36$. Downstream of reattachment, the wake recovery is evident from the spatial evolution of the velocity profiles. Fig. 7 (right) describes the spatial distribution of the mean velocity magnitude. From the contour plot, it is possible to clearly identify the pattern of the expansion followed by a plateau region of approximately uniform flow. The two free shear layers are displayed as streaks of densely spaced velocity contours merging at flow reattachment.

The dead air region delimited by the two free shear layers constitutes the separated flow, where reverse flow occurs with a maximum strength of 0.21$V_\infty$ at $x/h = 0.97$. Amatucci et al. (1992) found the reattachment location at $x/h = 0.89$ with a maximum reverse velocity of 0.23$V_\infty$ although their experiments were performed with different values of the Mach number on the two sides of the plate ($M_{1∞} = 2.05$, $M_{2∞} = 2.56$).
The Prandtl-Meyer expansion fan (outside of the boundary layer) is isentropic and the measurements can be assessed comparing the results with isentropic flow theory. The measured flow deflection is $\theta = 15.8^\circ$ in the plateau region downstream of the expansion fan where the corresponding velocity is $V_z = 580 \text{ m/s}$. The velocity ratio $V_z/V_\infty$ across the Prandtl-Meyer expansion solely depends on the Mach number upstream $M_\infty$ and the deflection angle $\theta$. The latter deflection angle is obtained evaluated by the velocity measurement. Table 1 shows that the measurement of the $V_z/V_\infty$ (and of $V_z$) agrees with IF theory within 0.4%. The comparison of measurement and theory for the Mach angle $\mu$ as obtained by the velocity contour plot returns a discrepancy of 1.7%.

In the second row of Table 1 the results of the measurement across the oblique shock wave are compared with theory. Given the Mach number upstream and the flow deflection, the normal velocity component is uniquely determined before and after the shock. The comparison agrees within 0.5%. The shock wave angle is also determined by shock wave theory and compared with the PIV measurement with a discrepancy of about 0.3 deg.

Table 1. Flow quantities across the oblique shock wave and expansion fan. Theory vs. measurement.

<table>
<thead>
<tr>
<th>Expansion fan</th>
<th>$M_\infty$ (meas.)</th>
<th>$\theta$ [deg] (meas.)</th>
<th>$V_z/V_\infty$ (meas.)</th>
<th>$\mu$ [deg] (meas.)</th>
<th>$V_z/V_\infty$ [ms$^{-1}$] (IF)</th>
<th>$\mu$ [deg] (IF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.99 ± 0.05</td>
<td>15.8 ± 5</td>
<td>(580 ± 4)/505</td>
<td>22.8 ± 0.5</td>
<td>578/505</td>
<td>22.42</td>
</tr>
<tr>
<td>Oblique Shock wave</td>
<td>$M_\infty$ (meas.)</td>
<td>$\theta$ [deg] (known)</td>
<td>$V_{nz}/V_{n\infty}$ (meas.)</td>
<td>$\beta$ [deg] (meas.)</td>
<td>$V_{nz}/V_{n\infty}$ [ms$^{-1}$] (OSW)</td>
<td>$\beta$ [deg] (OSW)</td>
</tr>
<tr>
<td></td>
<td>2.01 ± 0.05</td>
<td>11.31</td>
<td>1.52</td>
<td>40.6</td>
<td>1.528</td>
<td>40.57</td>
</tr>
</tbody>
</table>

Free shear layer structure

Fig. 8 describes the measurement of the mean velocity distribution in the free shear layer at a higher resolution than that of the complete base flow presented above. An average velocity distribution is obtained from an ensemble of 200 instantaneous snapshots. The FOV was 28 mm in the stream-wise direction of which only the center portion is shown. In the region between the end of the expansion and upstream of the recompression the outer flow Mach number is $M = 2.63$ and the convective Mach number (Papamoschou and Roshko, 1988) is estimated at $M_c = 1.04$. The transverse reference length scale is taken as the 10%-90% velocity thickness $b$ and the growth rate is evaluated along the $\xi$-direction that is aligned with the mean velocity after the expansion (inclined at 15.8$^\circ$ with respect to the $x$-coordinate). In the figure it is possible to observe the spatial development of both shear layers that surround the separated flow region. The velocity contour spreading rate is very limited and cannot be appreciated by visual inspection; nevertheless the velocity vector profiles reveal some details of the shear layer spatial evolution. The measurement yields $b = 2.3$ mm at $x/h = 0.75$ and a growth rate $db/d\xi = 0.062$, which compares satisfactorily with data from Petrie et al. (1986) who reported a growth rate of 0.064 in a backward facing step flow with an approaching Mach number of 2.43.
The spatial distribution of streamwise and vertical turbulence intensity is evaluated from the ensemble of 550 snapshots. The streamwise turbulence contour map shown in Fig. 9-left displays a local maximum along the shear layers approximately centered at the shear layer axis (inflection point in the mean velocity profile). The streamwise maximum is about 22% occurring around the reattachment region in agreement with earlier LDV results (Samimy and Addy, 1986). The local increase of the streamwise turbulence intensity is ascribed to the merging process and the mutual interaction of the free shear layers at the reattachment. The instantaneous flow analysis supports such a hypothesis, since a considerable interaction between the approaching shear layers is observed at the reattachment location. Downstream of the reattachment location the streamwise turbulence intensity decreases monotonically due to the wake recovery and to the flow recompression. However two distinct peaks can still be observed in the redeveloping wake.

The vertical turbulence intensity (Fig. 9-right) also increases along the separated shear layers and reaches a maximum before reattachment. Outside of the wake it is possible to observe a large region with weakly increased velocity fluctuations (5%), corresponding approximately with the area the recompression waves appear. Although the flow is uniform upstream of the recompression and outside of the shear layers, the unsteady reattachment causes the unsteady motion of the recompression waves, which results in a local increase of the velocity fluctuations. The increased fluctuation region is limited within a strip where the recompression waves are appearing. The same feature is not visible from the horizontal turbulence intensity distribution due to the small inclination of the recompression wave with respect to the x-axis. Weak disturbances can also be observed from the vertical turbulence intensity distribution emanating from the base edges corresponding to lip-shocks, which are also confirmed by HWA measurements.
Large-scale structures

Approaching the shear layer reattachment location and downstream of it, the flow undergoes a gradual recompression process with the development of the wake velocity profile. The flow accelerates at the centerline of the wake and the convective Mach number decreases from $M_c = 1.04$ upstream of the recompression to about $M_c = 0.64$ at $x/h = 2$ due to the wake recovery. At this abscissa the local wake thickness (90% velocity) is about 6 mm and the measurement conditions make it possible to access the large-scale turbulent structures with the present PIV resolution capability. At the given $M_c$ the stream-wise planar velocity survey is expected to yield the main features of large-scale structures evolving mostly as two-dimensional disturbances according to the work of Elliott et al. (1995) who reported that the mixing region is still dominated by Kelvin-Helmholtz rollers at $M_c = 0.51$.

Following the definition of Hussain (1986), a coherent turbulent structure is identified as a connected turbulent fluid mass with instantaneously phase-correlated vorticity over its spatial extent. The instantaneous velocity and vorticity snapshots return the direct evidence of coherent turbulent structures within the wake. Fig. 10 describes the flow organization at two different time instants. It is necessary to enlarge the view and to subtract the estimated mean convective velocity ($U_c = 320 \text{ ms}^{-1}$) in order to visualize the swirling motion corresponding to the vorticity peaks. From the picture on the top, it can be clearly seen that the large-scale fluctuations exhibit a roughly symmetrical arrangement with respect to the wake axis and counter-rotating structures oppose each other in most cases. The flow entrainment is a direct consequence of the swirling motion: downstream of each structure high speed flow is turned and directed towards the wake axis. Moreover back flow is induced in between counter-rotating structures, where the fluid is accelerated towards the base. The overall topology appears as a varicose wake instability mode, with a roughly symmetrical flow pattern with respect to the wake axis. Conversely, incompressible wakes flows develop into sinuous instability mode, typical of the von Kármán vortex street. The picture on the bottom reveals similar flow structures, however it is also possible to see that the whole wake axis exhibits large fluctuations in a flapping-like motion with amplitude comparable to the wake width. The development of the varicose mode wake instability is expected to originate from the unsteady behavior of the reattachment location, which requires further analysis of the present data.

The vorticity fluctuations occur with a relatively broad range of scales. The characteristic scale of the double rollers separation ranges from 1.5 mm to 3 mm depending on the strength and shape of the single structures. The size of a single structure is estimated to be between 0.5 mm and 1.5 mm (50% vorticity contour with respect to the peak value) from visual inspection of large sequences of velocity/vorticity fields at $x/h = 2$. Normalizing the results with respect to the local wake half width, the size of the single structures is in the range from 0.17 to 0.5. The planar visualization of large-scale turbulent structures by Bourdon and Dutton (1999) reported image correlation results yielding a structure normalized size of 1.15 at $x/X_r = 1.43$ and at a comparable $M_c$. The significant difference is ascribed to the fact that the planar visualization data are based on the Mie scattering shear layer thickness, which is about 40% of the thickness based on the velocity (LDV) profile as reported by the same authors.
The fluctuation strength is quantified with the vorticity peak value \( \omega \). Values occurring in the present measurements are on the order of \( \omega = 5 \times 10^5 \) s\(^{-1} \), which largely exceeds the value attained by the mean peak vorticity in the same region \( \omega_{\text{mean}} = 1 \times 10^3 \) s\(^{-1} \). The measured values of peak vorticity \( (1/\omega) = 2 \mu s \) also constitute an indirect assessment of the particle tracers response, confirming the estimate of \( \tau = 2.4 \mu s \). The present measurements are still regarded as a planar quantitative visualization of the instantaneous velocity/vorticity pattern. Its natural extension will be given by the statistical assessment of the turbulent coherent structure properties (eduction) by means of event detection/classification, phase alignment and ensemble average.

4. CONCLUSIONS

In the present study, PIV has been applied in a supersonic wind tunnel to describe the compressible turbulent flow of the wake behind a blunt-based two-dimensional body. Problems related with the application of PIV have been identified mostly in the seeding tracers response and in the limited spatial resolution associated to the size of the image interrogation window. The solid TiO\(_2\) particles performed adequately, yielding intense light scattering and being characterized by a relaxation time of only 2.4 \( \mu s \). The adoption of a cross-correlation based technique in combination with AR-WIDIM image processing allowed an increase in measurement resolution with respect to conventional cross-correlation analysis. Results describing the mean flow across the oblique shock wave and the isentropic flow accelerating around the base corner were in good agreement with theoretical predictions, according to shock-expansion theory. From the measurement technique standpoint the present investigation demonstrated that PIV allows the planar measurement of turbulent compressible flows with good accuracy at an acceptable resolution. The measurement uncertainty on the mean value was estimated on the order of 2 ms\(^{-1} \), while the error on the turbulence intensity was below 2% of \( U_\infty \).

The mean structure of the free shear was analyzed and the value of shear layer growth rate was obtained, which compared satisfactorily with literature data. However, due to technical limitations (spurious light reflections from the model base) the measurements could not be performed closer than 10 mm to the base. The flow turbulence measurement yielded the well-known features of separated base flows (turbulent shear layers, peaks around reattachment, redeveloping wake) as well as some less-investigated weak fluctuations due to the unsteady behavior of recompression waves. The unsteady turbulent structure of the redeveloping wake was analyzed in terms of instantaneous flow structures. Coherent structures were detected downstream of reattachment through inspection of the instantaneous vorticity pattern. The instantaneous velocity distribution obtained with respect to a Galilean reference frame moving with the estimated convective velocity confirmed the presence of masses of fluid in vortical motion. The coherent structures are organized as a double row and exhibit roughly elliptical shape. The observed structure size is less than the wake half width and the instantaneous peak vorticity is observed to exceed up to five times the value of the mean peak vorticity. The instantaneous planar vorticity measurements do not find direct comparison with literature data due to lack of similar experiments. It is therefore expected that further efforts be devoted to the statistical characterization of the large-scale structures in terms of coherent velocity and vorticity distributions.
REFERENCES


