PIV Measurements of a Shock Wave/Turbulent Boundary Layer Interaction

R.A. Humble¹, F. Scarano, B.W. van Oudheusden, M. Tuinstra

Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands
¹corresponding author: r.a.humble@tudelft.nl

Abstract  Particle Image Velocimetry is used to investigate the interaction between an incident planar shock wave and turbulent boundary layer developing on a flat plate at Mach 2.1. The mean velocity profile and deduced skin friction coefficient of the undisturbed boundary layer show good agreement with theory. A particle response assessment establishes the fidelity of the tracer particles. The interaction region is characterized by the mean velocity field, which shows the impinging and reflected shock wave pattern, as well as the boundary layer distortion. The unsteady flow properties are inspected by means of instantaneous velocity fields. Patches of reversed-flow are frequently observed at several locations. Although significant reversed-flow is measured instantaneously, on average no reversed-flow is observed. Turbulence properties show the highest turbulence intensity in the region behind the impingement of the incident shock wave. Turbulence anisotropy is found to be present, with the streamwise component dominating. A distinct streamwise-oriented region of relatively large Reynolds shear stress magnitude appears in the redeveloping boundary layer and persists downstream. The recovery of the boundary layer towards its initial equilibrium conditions therefore appears to be a gradual process.

1. Introduction

With the continued development of high-speed long haul civil transportation systems, as well as other high-speed manoeuvring vehicles, attention remains focused upon the problems of predicting the characteristics of shock wave/turbulent boundary layer interactions in high-speed flight. Numerous efforts over the decades have therefore sought to gain a better understanding of the complex behaviour of the shock wave/turbulent boundary layer phenomenon. A variety of studies considering planar interactions have been conducted (e.g. Holder et al., 1955, Chapman et al., 1958 and Green, 1970) which represent the internal interactions which typically occur within supersonic air intakes. These studies have mapped the mean flow properties as functions of Mach number and Reynolds number, as well as the incident shock wave strength and state of the undisturbed boundary layer.

Experimental studies of shock wave/turbulent boundary layer interactions have been generally frustrated however, by the limitations of the experimental techniques used (Dolling, 2001). Whilst hot-wire measurements and laser Doppler velocimetry have provided detailed information on the nature of turbulence in these flows, without whole-field quantitative information a complete characterization of the dynamical aspects of the flowfield cannot be made. Furthermore, whilst numerical simulations of these flows have achieved some degree of success, they have been generally hampered by the recognized deficiencies of the available turbulence models. It is generally accepted that conventional turbulence models can predict the mean flow properties of the interacting region reasonably well, but the accurate prediction of the associated turbulence properties still remains problematic (Knight and Degrez, 1998).

Advances in laser and digital imaging technology have led to the improvement of non-intrusive, planar flow diagnostic tools, such as Particle Image Velocimetry (PIV) in particular. This technique is capable of performing direct instantaneous velocity flowfield measurements making it suitable to investigate large-scale unsteady flow phenomena. Together with the ability to acquire large amounts of data, this technique offers the opportunity to investigate the spatial structure associated with shock wave/turbulent boundary layer interactions. PIV has historically found wide-spread application as a standard diagnostic tool in low-speed incompressible flows (Raffel et al., 1998). Efforts to extend this technique into the high-speed compressible flow regime became possible with the introduction of high-energy short-pulsed lasers, as well as short inter-frame transfer CCD captors. These efforts have been hindered however, by the technical difficulties associated with optical diagnostics in supersonic wind tunnels, namely; flow seeding, illumination and imaging.
Developments in image interrogation methods have increased the technique’s dynamic range (Scarano and Riethmuller, 2000), enabling particle motions to be measured in the presence of high-deformation rates with improved accuracy. The PIV technique has been applied to a variety of high-speed flow problems of practical interest, including wakes (Molezzi and Dutton, 1993), boundary layers (Glawe et al., 1996), as well as a number of shock wave/turbulent boundary layer interaction problems (e.g. Ünalmis et al., 2000, Beresh et al., 2002, Hou et al., 2003). These investigations however, have typically considered ramp or blunt-fin configurations. Comparatively few PIV studies have considered the impinging shock wave interaction (Haddad, 2005). The need for a better understanding of this type of flow, as well as the potential of non-intrusive measurement techniques provide the impetus for the application of PIV to the flow problem.

The subject of the following paper is to report on the application of PIV to the interaction between a planar incident shock wave and a turbulent boundary layer developing on a flat plate. A particle response assessment is made to establish the fidelity of the tracer particles under measurement conditions. The undisturbed boundary layer is characterized in terms of its mean and turbulence properties. Mean and instantaneous whole-field velocity measurements of the interaction region are obtained from which inferences about the turbulence properties are made.

2. Apparatus and Experimental Technique

2.1 Flow Facility

Experiments were performed in the blow-down transonic-supersonic wind tunnel (TST-27) of the High-Speed Aerodynamics Laboratories at Delft University of Technology. The facility generates flows in the Mach number range 0.5 to 4.2 in the test section. The test section dimensions are 280mm×270mm. The Mach number was set by means of a continuous variation of the throat section and flexible nozzle walls. Small deviations in Mach number were corrected for by automatic fine adjustment of the choke. The tunnel operates at unit Reynolds numbers ranging from 38×10^6 to 130×10^6 m⁻¹, enabling a blow-down operating use of the tunnel of approximately 300s.

Two types of experiment were conducted in the present study. Firstly, the undisturbed boundary layer was characterized in detail, followed by a main experiment to characterize the interaction region. The boundary layer along the wind tunnel top wall was considered in both cases. After naturally transitioning upstream in the nozzle, the boundary layer developed along a smooth surface under nearly adiabatic flow conditions for a development length of approximately 2m along the divergent part of the wind tunnel nozzle. A thick boundary layer is advantageous for PIV studies since it provides an increase in the scales of the mean and fluctuating flowfield, which allows to better resolve the interaction region. Upon entering the test section, the boundary layer was fully developed and exhibited smooth wall type behaviour. Experimental conditions are summarized in Table 1.

<p>| Table 1. Experimental conditions |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Undisturbed boundary layer</th>
<th>Interaction experiment</th>
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</thead>
<tbody>
<tr>
<td>$M_\infty$</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$U_\infty$, m/s</td>
<td>506</td>
<td>525</td>
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<tr>
<td>$\delta_99$, mm</td>
<td>20</td>
<td>20</td>
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<tr>
<td>$\delta^*$, mm</td>
<td>3.7</td>
<td>4.2</td>
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<tr>
<td>$\theta$, mm</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>$u_\tau$, m/s</td>
<td>19.5</td>
<td>19.5</td>
</tr>
<tr>
<td>$c_f$</td>
<td>$1.65\times10^{-3}$</td>
<td>$1.52\times10^{-3}$</td>
</tr>
<tr>
<td>$P_0$, kPa</td>
<td>225</td>
<td>280</td>
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<tr>
<td>$T_0$, K</td>
<td>278</td>
<td>284</td>
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<tr>
<td>$Re_\theta$</td>
<td>$3.36\times10^4$</td>
<td>$5.29\times10^4$</td>
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</table>

The displacement thickness $\delta^*$ and momentum thickness $\theta$ are the compressible values. The density variation was deduced from the velocity distribution using the adiabatic Crocco-Busemann relation with a constant recovery factor $r=0.89$, with the assumption that the static pressure in the transverse direction remains constant.
A 100mm long single-sided wedge with deflection angle of 10° was placed in the freestream to generate the incident planar shock wave. The generator was sting-mounted in the centre of the test section and spanned approximately 65% of the test section. A schematic representation of the experimental apparatus is shown in figure 1. Note that the sting has been omitted for clarity.

![Fig. 1. Schematic of experimental setup](image)

### 2.2 PIV Technique

Two-component PIV was employed in the present study. Flow seeding is considered one of the most critical aspects of PIV in high-speed flows. Titanium di-oxide (TiO₂) particles were adopted with a nominal median diameter of \( d_p = 50 \text{nm} \) and bulk density of approximately \( \rho_b = 1000 \text{kg/m}^3 \). A high pressure cyclone pressurized at 1000kPa generated the seeded stream, which was introduced into the settling chamber of the wind tunnel through a 2-D rake distributor. The seeding rake spanned roughly \( 26 \times 30 \text{cm}^2 \) and consisted of six vertical aerofoil type bars, each with six orifices. The seeded flow was illuminated by a Spectra-Physics Quanta Ray double-pulsed Nd:Yag laser with 400mJ pulsed energy and a 6ns pulse duration at wavelength 532nm. Laser light tunnel access was provided by a probe inserted downstream of the shock generator. The laser pulse separation in the boundary layer and interaction experiments was 0.6\( \mu \text{s} \) and 2\( \mu \text{s} \) respectively, which produced a particle displacement of approximately 0.3mm and 1mm respectively in the freestream flow. This corresponds to approximately 11 pixel maximum displacement in both cases. The light sheet was approximately 1.5mm thick. Particle images were recorded by a PCO Sensicam QE 12-bit Peltier-cooled CCD camera with frame-straddling architecture and a 1376×1040 pixel sized sensor. The sensor was cropped to 1376×432 given the large aspect ratio of the investigated flow region and at the same time to achieve an increased recording rate of 10Hz. A narrow-band-pass 532nm filter was used to minimize background ambient light. In the boundary layer experiment, the camera was rotated 90° to maximize the spatial resolution. Table 2 summarizes the PIV recording parameters.

<table>
<thead>
<tr>
<th>Test case</th>
<th>Parameter</th>
<th>Undisturbed boundary layer</th>
<th>Interaction experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field-of-view</td>
<td>5(W)×16(H)mm²</td>
<td>124(W)×39(H)mm²</td>
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<td></td>
<td>Interrogation volume</td>
<td>0.7×0.08×1.5mm³</td>
<td>1.9×1.9×1.5mm³</td>
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<td></td>
<td>Digital resolution</td>
<td>12( \mu \text{m/pixel} )</td>
<td>89( \mu \text{m/pixel} )</td>
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<tr>
<td></td>
<td>Recording distance</td>
<td>( z_0 = 15 \text{cm} )</td>
<td>( z_0 = 60 \text{cm} )</td>
</tr>
<tr>
<td></td>
<td>Recording lens</td>
<td>( f = 105 \text{mm}, \ f_b = 8 )</td>
<td>( f = 60 \text{mm}, \ f_b = 8 )</td>
</tr>
<tr>
<td></td>
<td>Pulse delay</td>
<td>0.6( \mu \text{s} )</td>
<td>2( \mu \text{s} )</td>
</tr>
</tbody>
</table>

The optical settings result in a particle image diameter \( d_\tau \) for the boundary layer and interaction experiment of \( d_\tau = 16 \mu \text{m} \) (2.4 pixels) and \( d_\tau = 13 \mu \text{m} \) (1.9 pixels) respectively. Both sets of recorded images were interrogated using the WIDIM algorithm (Scarano, 2002). This method is based upon the deformation of correlation windows with an iterative multi-grid scheme, which is particularly suited for highly sheared flows. A dataset of 475 images was acquired in the boundary layer and interaction experiments and were interrogated using windows of size 61×7 and 21×21 pixels respectively with an overlap factor of 75%.
The fidelity of the tracer particles was evaluated by considering their dynamic response when passing through a steady planar oblique shock wave (OSW). The OSW generated in the freestream of the interaction experiment was used for such an assessment. The PIV measurement returns the velocity spatial distribution making it possible to extract a velocity profile across the OSW. The velocity component normal to the shock wave was considered for this purpose. Figure 2 shows the distribution of the mean shock wave normal velocity along with the shock-normal abscissa $s$.

![Figure 2: Distribution of $u_n^*/u_{1n}$ across the OSW (Shock-normal abscissa $s$ is shown in yellow)](image1)

To assess the spatio-temporal response of the particles, the profile of the velocity is shown against $s$ in figure 3, where $s=0$ denotes the shock wave position. Here $u_{1n}$ and $u_{2n}$ are the upstream and downstream mean velocities respectively normal to the shock wave. Observe an appreciable distance before the particle velocity downstream of the shock wave reaches its reference value. The effects of a finite spatio-temporal resolution are also evident, where it can be seen that the velocity begins to decrease approximately one quarter of a window size upstream of the shock wave, as a result of the averaging effect intrinsic to the PIV interrogation method. The particle relaxation time $\tau_p$ was obtained with an exponential curve fit of $u_n^*/u_{0n}^*(s)$ and yielded $\tau_p=2.1\mu s$, corresponding to a frequency response $f_p=476kHz$. This value of $\tau_p$ is consistent with previous OSW particle response assessments using similar particles (Scarano and van Oudheusden, 2003). The present particle response behaviour can be compared with a modified Stokes drag law valid for small spherical particles. Given the relatively small particle Mach number and Reynolds number, the following drag relation to determine $\tau_p$ applies (Melling, 1986)

$$\tau_p = d_p^2 \frac{\rho_b}{18\mu_f} \left( 1 + 2.7Kn_d \right)$$  \hspace{1cm} (1)

where $Kn_d$ is the Knudsen number based upon $d_p$. An expression for the Knudsen number in terms of the Mach number and Reynolds number is provided by $1.26\sqrt{\gamma M_{\Delta u}/Re_d}$ (Schaaf and Chambre, 1958) where $\gamma$ is the ratio of specific heats, taken as $\gamma=1.4$ for air. The Mach number $M_{\Delta u}$ is based upon $\Delta u$ the maximum particle slip velocity, which occurs downstream of the shock wave and was determined to be $M_{\Delta u}=0.38$. The downstream Reynolds number based upon $d_p$ was determined to be approximately $Re_d=1$. This results in a relaxation time $\tau_p$ of less than $1\mu s$. The discrepancy between this result and the measured result is ascribed to particle agglomeration, a phenomenon which introduces an uncertainty on the effective particle size and hence response characteristics. Inserting the experimentally determined $\tau_p$ back into Eq. 1 gives an effective particle agglomerate diameter of approximately $d_p=0.41\mu m$, a value significantly greater than the nominal median diameter of $d_p=50nm$. The particle dynamic effects can be further parameterized by the Stokes number $S_t$, defined as the ratio between $\tau_p$ and a time scale of the flow $\tau_f$. For accurate flow tracking at the time scale represented by $\tau_f$ it is necessary to meet the criterion that $S_t<<1$. Assuming a flow time scale of $\delta/U_\infty$ then this gives $\tau_f=38\mu s$. The corresponding Stokes number is therefore 0.06 which is consistent with a high-speed turbulent shear layer investigation (Urban and Mungal, 2001).
3. Results and Discussion

3.1 Undisturbed Boundary Layer

The van Driest effective velocity concept is used to give a suitable description of the compressible turbulent boundary layer velocity profile within the log-law region (White, 1991). The non-dimensional velocity $u^+$ and length scale $y^+$ normalized with the friction velocity $u_\tau$ are defined as

$$u^+ = \frac{\overline{u}}{u_\tau}, \quad y^+ = \frac{u_\tau y}{v_w}, \quad u_\tau = \sqrt{\frac{\tau_w}{\rho_w}}$$

(2)

where $v$ is the kinematic viscosity, $\tau$ is the shear stress, $\rho$ is the density and the subscript $w$ denotes the wall condition. The mean experimental velocity profile $\overline{u}(y)$ determined from the boundary layer experiment is transformed into an effective velocity $u_{eq}$ using the van Driest compressibility transformation, given for an adiabatic flow by

$$u_{eq} = \frac{U_e^*}{a} \sin^{-1}\left( a \frac{\overline{u}}{U_e^*} \right) = u_\tau \left( \frac{1}{\kappa} \ln y^+ + B \right) \quad \text{where} \quad a = 1 - \frac{T_e}{T_{aw}}$$

(3)

Here $T$ is the temperature with constants $\kappa=0.41$ and $B=5.0$. The subscripts $e$ and $aw$ denote the boundary layer edge and adiabatic wall conditions respectively. The right-hand side of Eq. 3 is the ordinary incompressible form of the law-of-the-wall; the left-hand side is the effective velocity. The corresponding law-of-the-wall fit for the present experimental data is shown in figure 4. The statistical uncertainty associated with the mean velocity $\overline{u}$ is estimated to be approximately $0.3\%U_\infty$. The experimental effective velocity profile coincides with the theoretical profile when a friction velocity of approximately $u_\tau=19.5\text{m/s}$ is assumed. The corresponding skin friction coefficient determined from $c_f = \frac{2 u_\tau \rho}{\rho_e U_e^2}$ gives $c_f = 1.61 \times 10^{-3}$.

Within the logarithmic region there is excellent agreement between the experimental data and the van Driest effective velocity. Spalding, (1961) has provided a single composite formula for the entire wall-related region and is given by

$$y^+ = u^+ + e^{-\kappa B} \left( e^{\kappa u^+} - 1 - \kappa u^+ - \frac{1}{2} \left( \kappa u^+ \right)^2 - \frac{1}{6} \left( \kappa u^+ \right)^3 \right)$$

(4)

A slight departure of the experimental data from the single composite formula can be observed for approximately $y^+<30$. Here the lower edge of the interrogation window becomes influenced by the presence of the wall. The closest point to the wall however, lies within the linear sub-layer ($y^+<5$). To the author’s knowledge, PIV measurements within the linear sub-layer of a supersonic boundary layer have never been made. A wake component, characteristic for turbulent boundary layers, can also be identified. The Coles wake parameter $\Pi$, which is used to help describe the deviation of the outer layer profile from the law-of-the-wall was determined to be $\Pi = 0.45$, which is in reasonable agreement with the value of 0.55 commonly admitted for zero-pressure gradient incompressible boundary layers when $Re_\theta>5000$ (Cebeci and Cousteix, 1999). It should be noted that $\Pi$ varies with boundary layer history and somewhat with Mach number.

The variation of the streamwise $<u'>$ and transverse $<v'>$ turbulence intensity, as well as the Reynolds shear stress $\overline{u^'v'}$ is shown in figure 5, where $<>$ denotes the root-mean-square quantity. The statistical uncertainty associated with the turbulence intensity and Reynolds shear stress is estimated to be approximately $3\%$ and $<10\%$ respectively. Data points are shown spaced at a maximum distance of $3\%$ of the figure. The compressible momentum thickness is chosen to scale the wall-normal coordinate because it can be determined more accurately than the boundary layer thickness. From these results the freestream turbulence cannot be determined. All profiles vary appreciably within the boundary layer, with $<v'>$ and $\overline{u^'v'}$ reaching maximum values of $2\%$ and $0.075\%U_e$ respectively at approximately $y^+/\theta=2.5$. The variation of $<u'>$ is quantitatively similar to turbulence measurements made within a variety of supersonic boundary layers (e.g. Petrie et al., 1986, Johnson, 1974), as well as those obtained by means of PIV (Hou et al., 2002).
3.2 Mean Flow Properties

An instantaneous PIV recording from the interaction experiment is depicted in figure 6 and shows a non-uniform seeding concentration due to the density variation within the flow. The incident and reflected shock waves can be visualized, whilst the boundary layer is highlighted by a comparatively lower seeding level. Turbulent activity within the downstream boundary layer can be seen, as well as the intermittent nature of the boundary layer edge. Laser light reflections were minimized during the experiments by illuminating almost tangent to the wall.

The mean flow behaviour is described by the averaged streamwise velocity field in figure 7. Velocity vectors are under-sampled in the streamwise direction for clarity. The origin of the reference coordinate system is located on the tunnel wall with \( x \) measured in the downstream flow direction from the extrapolated wall impact point of the incident shock wave and \( y \) normal to the wall. The incident and reflected shock waves are visible as a sharp flow deceleration and change of direction for the first; whereas the reflected shock wave exhibits a smoother spatial variation of the velocity due to its unsteady nature and the averaging effect. From the mean velocity vectors, no reversed-flow can be detected, although it appears that the flow is close to separation. This lack of mean flow separation may be ascribed to the fact the shock generator is not full-span and therefore the consequent three-dimensional relieving effect may have weakened the interaction. Downstream of the interaction region, the distorted boundary layer has approximately doubled its thickness and develops with a relatively low rate of recovery.
3.3 Two-Dimensionality of the Flowfield

To examine the effects of spanwise non-uniformities that are often present in nominally two-dimensional flows, PIV measurements were made at several spanwise locations in increments of $z/\delta = 0.5$ with 50 images acquired at each location. Recording and interrogation settings were the same as those used in the interaction experiment. Figure 8 shows iso-surfaces of Mach numbers 0.5, 1.0 and 1.5, determined by assuming the flow to be adiabatic. It can be seen that relatively little change in Mach number occurs with spanwise variation. The rapid dilation of the subsonic layer is also evident. The inset illustrates that although slight three-dimensional effects appear to exist within the separated flow region, they seem characteristic of the fluid dynamic processes present and not due to the sidewall boundary layers. Mean flow properties show appreciable differences however, at distances greater than 30% of the test section width. This behaviour is ascribed to both the limited span of the shock generator, as well as the increasingly intermittent nature of the incoming seeded streamtube.

![Fig. 8. Spanwise survey of the interaction region](image)

3.4 Instantaneous Results

The instantaneous velocity snapshots reveal several interesting features associated with the unsteady behaviour of the interaction region. Figure 9 illustrates fields of the instantaneous streamwise velocity. The time that elapses between consecutive recordings (10Hz framing rate) is significantly greater than any characteristic flow time scale, leading to a series of uncorrelated velocity snapshots. It can be seen that the outer freestream flow remains steady and there appears to be no appreciable motion of the incident shock wave. The global structure of the interaction region however, varies considerably in time. Specifically, the reflected shock wave appears to be highly unsteady, as well as the upstream boundary layer, which has a clearly intermittent nature.

Regions of reversed-flow frequently occur in the interaction region of the order $-0.1U_\infty$. In other cases however, the flow remains fully attached with no observable reversed-flow. On average no reversed-flow is observed. The separated flow region experiences distortions mostly in the streamwise direction, although motion is also observed in the transverse direction. Qualitatively, at least in some instances, the reflected shock wave appears to be displaced away from the wall when the size of the reversed-flow region increases, and moves towards the wall when the size of the reversed-flow region decreases. This would suggest that the large-scale motion of the separation shock wave is associated with the shock’s displacement due to the expansion and contraction of the separated flow region. This agrees with previous related studies (Erengil and Dolling, 1993) which examined a hypersonic two-dimensional compression ramp interaction. It is now clear that the mean flow organization is in fact a somewhat simplified representation, since it is constructed from a statistical analysis of an instantaneous flowfield that is highly fluctuating and significantly more complex.
3.5 Turbulence Properties

Figures 10a and 10b show the distributions of $<u'>$ and $<v'>$ respectively. A substantial increase in $<u'>$ occurs throughout the interaction region, initiating itself within the reflected shock foot region, and reaching a maximum value of approximately $0.21U_\infty$ underneath the incident shock wave’s intersection with the sonic line. This value is comparable to laser velocimetry measurements (Moderass and Johnson, 1976, and Meyer et al., 1997) as well as Large Eddy Simulation (LES) computations (Garnier and Sagaut, 2002) which have all considered an impinging shock wave interacting with a flat plate turbulent boundary layer. The increase in the streamwise component is over 100% greater than the increase in the transverse component indicating that appreciable turbulence anisotropy is present. The streamwise component however, can be seen to recover much more quickly than the transverse component further downstream due to the redistribution of turbulent kinetic energy mainly through the pressure-strain correlation (Ardonceau, et al., 1980).

The higher level of fluctuations associated with the impinging shock wave (approximately 4%$U_\infty$) is typically encountered in these experimental conditions and is ascribed to the combined effect of the decreased measurement precision and to small fluctuations of the shock wave position. The reflected shock wave exhibits a relatively high level of fluctuations, which in this case should not be regarded as turbulence but is ascribed to its unsteady motion. The increased level of fluctuations across these shock waves within the boundary layer is thought to be associated with their interaction with the convection of turbulent coherent structures, as well as their increased unsteadiness. It is striking how the turbulence intensity distributions reveal the curvature of both shock waves in this region. Two weak features downstream of the reflected shock wave (one parallel and the other roughly perpendicular to it) can also be observed in both the streamwise and transverse components. These features are thought to be due to optical aberration effects introduced by the inhomogeneous index of refraction field of this compressible flow (Elsinga et al., 2005).
Profiles of \( <u' > \) and \( <v' > \) throughout the interaction region are shown in figure 11. The poorer spatial resolution compared to the boundary layer experiment is evident. Within the first part of the interaction, a substantial increase in both components occurs, particularly in the streamwise component as previously observed. The presence of the incident and reflected shock waves is also evident at this location, where local maxima occur in the outer part of the boundary layer. It is now clear that within the interaction region, the typical boundary layer assumption of a sufficiently small transverse pressure gradient (\( \frac{\partial p}{\partial y} \approx 0 \)) may no longer be valid since there is now an appreciable variation of the transverse velocity fluctuations normal to the wall.

\[ \text{Fig. 11. Turbulence intensity profiles, a) } <u'/U_\infty, \text{ b) } <v'/U_\infty \]

Consider now the Reynolds shear stress distribution. Such measurements are principally carried out to aid the modelling of turbulent effects by computational methods. They are of particular importance in the validation of turbulence closure models since theoretical efforts are generally hampered by the difficulties of representing the turbulence terms in the time-averaged equations. For compressible flows, the effective Reynolds shear stress is conventionally expressed by \( \bar{\rho} \bar{u'} \bar{v'} \) when the density fluctuations are ignored. For practical purposes, the term \( \bar{u'} \bar{v'}/U_\infty^2 \) will be regarded as being representative of the Reynolds shear stress. The spatial distribution of \( \bar{u'} \bar{v'}/U_\infty^2 \) is shown in figure 12.

\[ \text{Fig. 12. Reynolds shear stress distribution } \bar{u'} \bar{v'}/U_\infty^2 \times 10^3 \]

Initially moderate levels of \( -u'v' \) are present within the undisturbed boundary layer, with a substantial increase in Reynolds shear stress magnitude occurring within the incident and reflected shock foot regions. The increase in turbulence in these regions is expected since it is known that supersonic flow which undergoes a compression is associated with turbulence augmentation. Although there appears to be a systematic change of Reynolds shear stress within the separated flow region, its behaviour at this point is unclear. The redeveloping boundary layer can be characterized by the presence of a distinct streamwise-oriented region of relatively large Reynolds shear stress magnitude in the lower part of the boundary layer. Note the overwhelmingly negative values in this region, indicative of slower moving \( (u'<0) \) upward-oriented \( (v'>0) \) fluid, and faster moving \( (u'>0) \) downward-oriented \( (v'<0) \) fluid relative to the mean flow.
As noted by (Ardonceau, 1983) who studied the structure of turbulence in shock wave/boundary layer interactions, these large Reynolds shear stresses imply the existence of large-scale eddies, consistent with the instantaneous results in the present study, and are also indicated by the recovery of the downstream boundary layer velocity profile. The recovery of the turbulence properties however, appears to be a very gradual process, with the current field-of-view insufficient to observe the boundary layer returning to its initial equilibrium conditions.

4. Conclusions

PIV has been applied to a shock wave/turbulent boundary layer interaction on a flat plate. A particle response assessment established that the fidelity of the tracer particles was consistent with similar studies. The mean velocity profile and deduced skin friction coefficient of the undisturbed boundary layer showed good agreement with theory. The interaction region was characterized by the mean velocity field, which showed the impinging and reflected shock wave pattern, as well as the boundary layer distortion. The unsteady flow properties were inspected by means of instantaneous velocity fields. Patches of reversed-flow were frequently observed at several locations. Although significant reversed-flow was measured instantaneously, on average no reversed-flow was observed. Turbulence properties showed the highest turbulence intensity in the region behind the impingement of the incident shock wave. Turbulence anisotropy was also found to be present, with the streamwise component dominating. A distinct streamwise-oriented region of relatively large Reynolds shear stress magnitude appeared in the redeveloping boundary layer. Boundary layer recovery was observed to initiate downstream of the interaction region. Its recovery towards the initial equilibrium conditions however, appeared to be a gradual process.

References


