Wall shear stress measurements in a turbulent wall-jet using MPTV

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Abstract In this paper we present the application of the Mirror Particle-Tracking-Velocimetry on the near-wall flow in a turbulent wall jet. The MPTV technique was presented at the PIV 2007 conference by Kunze et al. for the laminar wall-jet. The basic principle is the use of a reflective coated surface to record the flow in the very near wall region. The original particle image and its mirror image are detected. By using a high-speed laser- and camera-system the temporal resolution of the mirror PTV technique was extended to frequencies in the region of 500Hz. Therefore, we were able to record typical structures appearing while the laminar-turbulent transition.

1. Introduction

The spatial and temporal distribution of wall-shear-stress (WSS) or skin friction is a direct footprint of the near wall flow dynamics and flow separation. Its visualization provides a direct visual impression of the dynamics of separation features, flow reattachment and near wall coherent structures interacting with the wall. In practice the simultaneous measurement of the WSS distribution at a multitude of points and its temporal fluctuation is still difficult to achieve with today’s techniques. Conventional methods to measure the wall flow features such as oil-film interferometry or liquid crystal imaging are lacking in quantitative and temporal resolution. The idea of the MPTV is to use the spacing of the particle image and its mirror image in the image plane to calculate the distance of the particle relative to the wall with high accuracy. Combined with the information from the particle displacement between successive illuminations it is possible to determine the WSS with high temporal and spatial resolution. The technique uses a strip-coded light-sheet and a camera set-up with telecentric lenses. The light-sheet plane is oriented parallel and very close to the wall.

The basic principle of the technique is illustrated in figure 1. A single particle in the flow is detected two times by each camera. One image is the results of the scattered light coming directly from the particle itself (real image), the second image results from the light reflected by the mirror (mirror image). This leads to a typical pattern of a particle image pair consisting of a real and a mirror image. Since telecentric optics are used, the recorded images have negligible perspective distortion and a parallel projection is justified for the following arguments. Then, the coordinates of the particle images (real and mirror) obtained by cameras, \(X_1, X_2\) and \(Y_1, Y_2\), can be used to calculate the position of the particles in all coordinates \(x, y, z\), equations 1.
Fig. 1 Sketch of the basic principle shown for a stereo camera set-up with an angular displacement of 90°. The image shows a span wise cross-section through a boundary layer flow over a reflective coated surface with the mean flow perpendicular to the paper plane. The image planes are tilted into the paper plane. The light gray shaded regions represent cross-sections of the strip-coded light-sheet and the regions shaded in dark gray represent the dark stripes in the images without any particle images; A,B real images; A’,B’ mirror images of the particles. For simplicity, the complex ray-tracing has been omitted since we are using telecentric lenses.

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\begin{align*}
    x(A) &= M \cdot x_1(A) = M \cdot x_2(A) \\
    y(A) &= M \cdot \cos(\alpha) \cdot \sqrt{y_1(A) + y_2(A)} \\
    z(A) &= M \cdot \sin(\alpha) \cdot (y_1(A) - y_1(A')) = M \cdot \sin(\alpha) \cdot (y_2(A) - y_2(A'))
\end{align*}
\]

(1)

An illustrative example of particle motion in the very near wall region is demonstrated in figure 2. In figure 2a a cut out of 9 superposed images is given and in figure 1b the corresponding 3D plot of the particle positions is illustrated.

Fig. 2 Example of the particle motion and the calculated 3D position, for a recording frequency of 500Hz

To prove the accuracy of the MPTV, the distribution of the wall-shear-stress in a laminar wall-bounded jet was determined and compared with the theoretical solution according to Glauert. The experimental results were presented at the PIV 2007 conference by Kunze et al. and show a good agreement with the theoretical solution, figure 3. The goal is to record structures appearing while the laminar-turbulent transition, e.g. hair-pins.
Fig. 3 Distribution of the wall shear stress along the surface of the mirror for three different Reynolds numbers at the downstream end of the mirror (x=48mm) of $Re=24000$, $40000$, $52000$; lines: theoretical solution of Glauert (1956) for a laminar wall; symbols: mean-value of the measurements; standard deviation $\sigma = 1.54 \text{ mPa}$

2. Experimental set-up

In contrast to the results presented at the PIV 2007, the nozzle is orientated horizontally and the water jet exits the nozzle parallel to the wall, figure 4.

Two CCD-cameras were positioned with an angular displacement of 90° symmetric to the normal to the wall. A plane surface mirror element was mounted flush with the surface. The light-sheet was oriented parallel to the wall and was partially blocked by a grid to achieve a strip-coded illumination. This reduces the overlap of real- and mirror-images and enhances the reconstruction quality. The light-sheet is formed from the beam of a 10mJ Nd: YLF High-Speed laser with double-lens optics so that the focus width of the light-sheet has a minimum of 500 µm at the position of the mirror. Two Photron Fastcam APX RS cameras with a resolution of 1024x1024 pixels at a frequency of 500 Hz were used to record the images. Near the exit of the nozzle the flow is laminar and develops to a fully developed turbulent flow further downstream. The mirror PTV provides the particle velocity in addition with the accurate value of wall-normal distance. It allows detecting particle motion as close as 50 µm near the wall. The stream wise component of wall-shear-stress can be determined with a single camera with high accuracy and high spatial and temporal resolution over larger surfaces. The temporal resolution only depends on the temporal resolution of the laser and
recording system. The flow was disturbed by slits. Therefore, the velocity at the nozzle exit is randomly distributed in span wise direction, figure 5.

Fig. 5 Photograph of the nozzle with indicated exit flow

3. Results

The flow field was measured with standard PIV to validate the results of the wall-shear-stress measurements. Figure 6a illustrates a colour-coded plot of the time averaged 2D stream-wise velocity distribution in a plane parallel to the mirror surface. Two elongate areas of high velocity separated by an area of lower velocity in the middle of the plot are visible. These areas of high velocity appear as two peaks in the velocity plot along the span wise direction of the flow, figure 6b. These structures in the flow field can be explained by the disturbance of the flow at the nozzle exit and correspond with the configuration of the slits at the nozzle exit.

Fig. 6 Time averaged velocity field measured by PIV
The time averaged wall shear stress distribution is shown in figure 7. Obvious are the dark blue stripes of zero wall shear stress. These stripes are caused by the lack of information in the dark stripes of the strip-coded-light sheet. The locations of the two peaks in Figure 8 correspond with the local maxima in Figure 6b.

While the laminar-turbulent transition characteristic patterns occur in the flow, e.g. hair-pins. A particle at the front of a hair pin is pushed down, see the blue points in figure 9. A particle at the back side is pushed up, see the red points in figure 9. Furthermore, the higher velocity of the pushed down particle leads to a peak in the wall shear stress indicating a characteristic foot print of a hair-pin structure.

To identify a hair-pin in the flow, at first the 3D particle motion was used to identify the characteristic motion pattern. Figure 10 illustrates the particle motion in a cut-out of the field of view of 25 superposed images. The time is colour-coded to imagine the particle motion. Therefore, points with the same colour were recorded at the same time in the region from blue $= t_0$ to red $= t_0 + 50$ms. A typical pattern of the particle motion is marked by the black ellipse in the middle of the image, figure 10a. Figure 11 shows the marked pattern in an independent coordinate system. The motion direction is indicated by two arrows. Obviously the particle motions in figure 11 are similar to those in a hair-pin structure, figure 9.
To prove the correct interpretation of this motion pattern as a hair-pin the colour-coded velocity and wall shear stress plots are shown in figure 12 and figure 13 (velocity and wall shear stress increase from blue to red). The colour-coded plot provides only a qualitative impression. The area of the motion pattern is marked with a black ellipse. The particle on the
left hand side has a higher velocity than the one on the right hand side. It is decelerated because its wall normal distance decreases. Nevertheless, this local decent of a particle with high velocity causes a peak in the wall shear stress, indicated by the dark red points in figure 13. This peak of the wall shear stress is a typical indication of a hair-pin structure.

Fig. 12 Plot of the 2D particle positions for 25 superposed images, colour-coded velocity

Fig. 13 Plot of the 2D particle positions for 25 superposed images, colour-coded wall shear stress
4. Conclusion

The aim of this work is the identification of typical structures appearing while the laminar-turbulent transition. Therefore, a disturbed wall-jet flow was generated by a horizontally orientated nozzle. Standard PIV was used to measure the velocity in a plane parallel to the mirror surface. The comparison between these results and the velocity distribution measured with MPTV yields good agreement. The 3D particle motion plot was used to identify typical motion patterns generated by a hair-pin structure in the flow. Afterwards the velocity and wall shear stress distribution at the area of interest were used to prove the correct interpretation of the motion pattern. With the information of the 3D motion plot, the velocity distribution and the wall shear stress distribution at least one hair-pin structure was found in a time interval of 50ms.

References

