Flow Separations Generated by a Simplified Geometry of an Automotive Vehicle

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1. Introduction

The aerodynamic forces on road vehicles are the result of complex interactions between flow separations and the dynamic behavior of the released vortex wake. Successful future car design needs to take advantage of these interactions to improve flow control by means of active or passive control devices. Detailed knowledge of the physical mechanisms involved in the formation of flow separations and their interactions with vortex wakes are necessary to achieve this objective. Most previous studies used simplified car models, as for example the Ahmed body [1,3,5] in combination with wind tunnels to study these mechanisms. The flow around this body reproduces the basic aerodynamic features of cars on a well-defined simplified geometry that favors the comparison between different experimental and numerical studies [1,2]. Measured quantities are the structure of the skin-friction lines and the time-averaged velocity field in the wake flow [1,3,5]. However, such time-averaged single point measurements give only limited information on the structure of the near wake flow and its dynamical behavior [1,3]. In this study we analyze both, the structure of flow separations on the body itself and the vortical structures in the near wake. At this end we take advantage of a low-speed water tunnel which allows to use visualizations techniques in combination with ordinary video acquisition equipment.

2. Experimental arrangement

The experiments were conducted in a closed water tunnel. The test-bed had a rectangular cross-section of 0.5 x 0.25 m^2 and a length of 1.4 m. The upper limitation of the test section was left open with a free surface. The flow speed varied between 0.10 m/sec and 0.30 m/sec with $3x10^4 = Re = 9x10^4$, where the Reynolds number is based on the length of the Ahmed body (Figure 1 and 2). All sidewalls were made of clear Perspex to allow flow visualization. In addition a lateral water evacuation by cyclones permitted to observe the flow through the endwall of the test-section in the upstream direction. The flow was visualized with the help of the electrolytic precipitation technique [4]. Flattened solder wires (width 3 mm, thickness 0.08 mm) were fixed on the model surface and supplied with constant voltage between 2-5 Volts depending on the electrical conductivity of the water in the test-bed. The continuously released white powder marked streak surfaces which left the boundary of the model at discrete flow separations. Inside the flow the tracer was convected with the wake flow indicating the position and dynamical behavior of vortical structures. The topology of the flow field could be either studied in discrete, well positioned 1 mm thick sheets of light (5 Watt Argon laser in combination with a cylindrical lens) or in the flood light of three halogen lamps (3x50 Watt). The first method was used to study the evolution of vortex structures in a longitudinal plane or in successive transversal sections, while the second method allowed to observe simultaneously both, vortical structures inside the flow and skin friction lines on the surface of the model. All these observations were recorded on SVHS tape and then digitized in order to obtain spatial and temporal information.

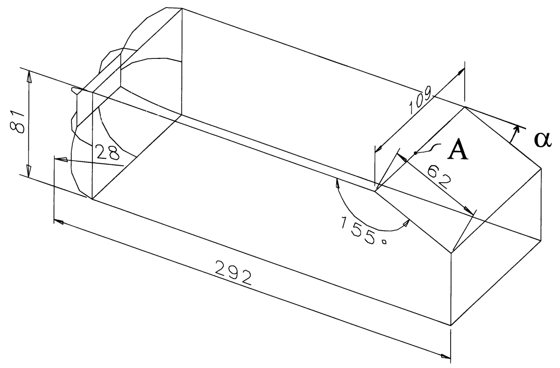

Figure 1 – Geometry of the Ahmed body at scale 0.28; α slant angle.

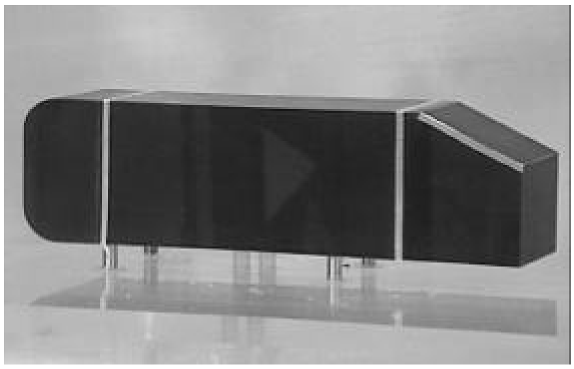

Figure 2 – Arrangement of the flattened solder wires on the surface of the Ahmed body.

3. Observations on the Structure of Flow Separations

The experiments presented bellow were carried out for a slant angle α of 25 degrees at a velocity of 0.1 m/sec corresponding to a Reynolds number of about $3x10^4$. Both flow separations on the front and rear part were examined.

3.1. FLOW SEPARATIONS ON THE FRONT PART

The figures 3-6 show the structure of the flow separations on the roof of the front part. The skin-friction lines in figure 3 show the existence of a separation line, which ends laterally in two foci. In figure 4 white tracer concentrations around these foci indicate that they are at the origin of two counter rotating longitudinal vortices. These vortices are linked by transversal vortices similar to Kelvin-Helmholtz vortices, as illustrated by figure 5 taken in a vertical sheet of light

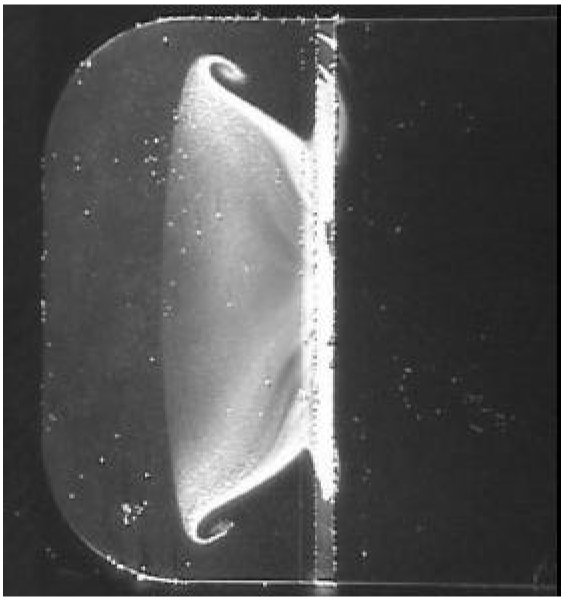

Figure 3 – Skin-friction lines in the separation zone of the front part. View from above with white light.

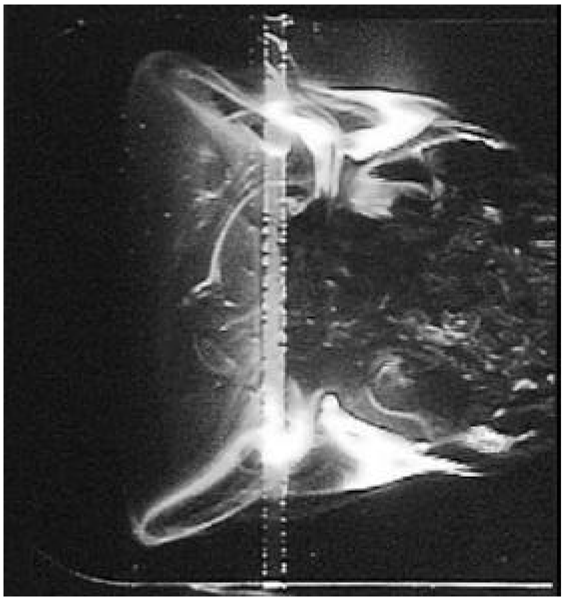

Figure 4 – Flow structure in the separation zone of the front part 3 mm above the boundary of the model. View from above. Illumination by a 1 mm thick horizontal laser light sheet.

Figure 5 – Side view of the flow structure in the separation zone (middle plane). Vortical structures of the Kelvin- Helmholtz type are visible.

Figure 6 – Cross-section through the separation zone of the front part 70 mm downstream of the front panel. View from behind in the upstream direction. Longitudinal vortices are visible at the right and left lateral limitations of the separation zone.

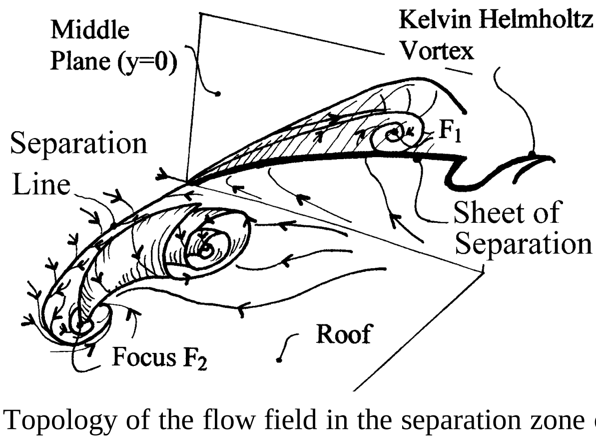

Figure 7 – Topology of the flow field in the separation zone of the front part. Counter rotating longitudinal vortices arise from the foci F_1 and F_2.

along the plane of symmetry. These two vortices are also visible in a vertical transversal plane 70 mm downstream of the front panel (Figure 6). Sequences of such images show that the volume of the separation region pulsates with a frequency of about 0.21 Hz, leading to periodic in- and outflow. In contrast the transversal vortices are released with a more than ten times higher frequency of about 2.8 Hz. Similar separation zones exist on the sidewalls of the front part. The resulting topology of the separation zone is summarized in figure 7. The foci F1 and F2 are at the origin of the longitudinal vortices visible in the cross-section, shown in figure 6.

3.2. FLOW SEPARATIONS ON THE REAR PART

The figures 8-13 show the structure of the flow separations on the hatch panel. In the central part of the panel the tracer distribution, figure 8 indicates a reversed flow direction towards the roof corner. Along the sidewall corners the flow moves also upstream towards the roof. Between these regions two dark oval shaped zones persist even after very long observation times suggesting the absence of significant velocities near the boundary in this region. Upstream of the corner with the roof panel the tracer is convected towards the central plane of symmetry of the model. This inward motion is also visible in a cross-section perpendicular to the main velocity 20 mm upstream of the roof corner (Figure 9). More downstream on the hatch panel the fluid turns back towards the side corners and is sucked into the longitudinal vortices, as shown for the left trailing vortex in figure 10. The position of these strong trailing vortices above the hatch panel implies the existence of an attachment line, which can be seen on the left side of figure 12 as black channel. The resulting topology of the separation zones is summarized in figure 14. In particular we remark that our observations suggest the existence of an attachment zone N_1. While the flow near the upper corner is

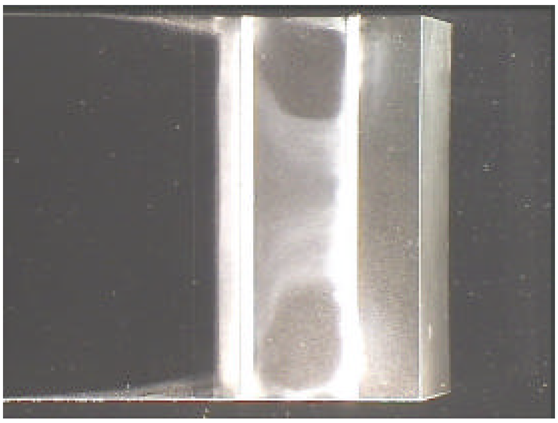

Figure 8 – Time averaged skin-friction lines on the hatch panel. View from above with white light.

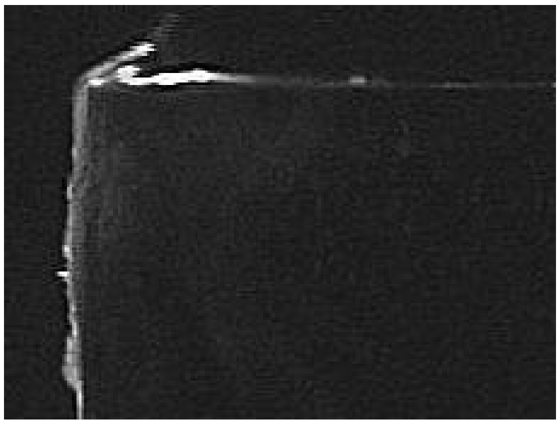

Figure 9 – Unsteady flow around the corner between left sidewall and roof. Vertical light sheet 20 mm upstream of the corner between roof and hatch panel. View from behind.

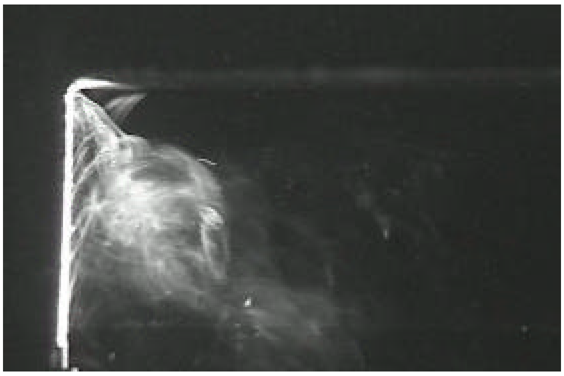

Figure 10 – Trailing vortex arising at the sidewall of the hatch panel. Only the left side is shown. View from behind in the upstream direction. Illumination by white light.

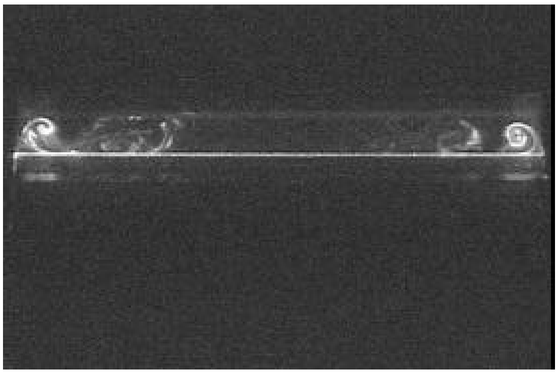

Figure 11 – Rolling-up of the lateral trailing vortices. Cross-section 25 mm downstream of the roof corner. View from behind in the upstream direction.

Figure 12 – Flow field adjacent to the hatch panel in a light sheet of 1 mm thickness parallel to the panel. View from behind in the upstream direction.

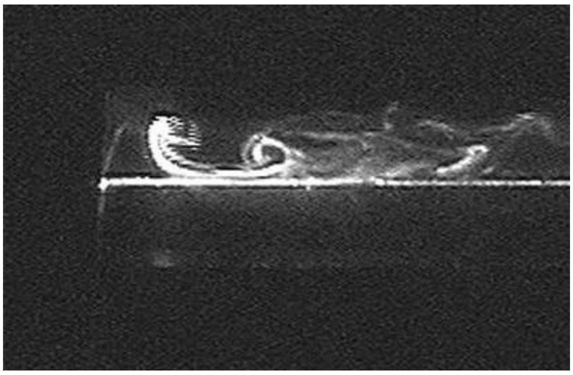

Figure 13 – Flow structure near the attachment line in a transversal cross-section 20 mm downstream of the corner between roof and hatch panel. View from behind in the upstream direction.

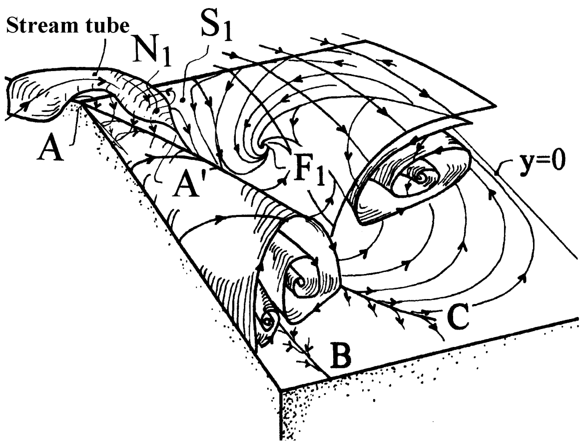

Figure 14 – Topology of the streamlines in the separation zone of the hatch plane (only the left side is represented). AB separation line of the secondary vortex. A'C attachment line of the main vortex. The saddle point S_1 separates the attachment point N_1 and the focus F_1.

remarkably steady, the flow closer to the end of the hatch panel becomes highly unsteady. The unsteadiness is due to oscillations of the trailing vortices themselves and interactions with vortices shed from the front.

4. Conclusion

The visualizations indicate how the vortical structures inside the near wake arise from flow separations. In the front part the separation zones are open with periodic vortex shedding. Although the dimensions of this region tend to decrease with increasing Reynolds number, the shedding will persist and cause detrimental effects like sound generation and unsteady interaction with the vortical structures arising from the hatch panel. The rear part separation zone appears to be more complex than previously found by Ahmed *et al* [1]. In particular we found an additional region of attachment in agreement with previous numerical simulations [2]. Furthermore the central detached flow region is not closed but contains two separation foci, which slowly evacuate the fluid above the panel into the wake.

Although the experiments were carried out at Reynolds numbers of about $3x10^4$ the position and topology of the flow structure are in good overall agreement with previous studies at Reynolds numbers of $O(10^6)$ [1,3,5]. The use of low speed water tunnels in combination with flow visualizations appears to be a useful tool to complete wind tunnel studies.

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