PIV measurement of the flow past a generic car body with wheels at LES applicable Reynolds number

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Abstract

Experiments by using 2D–2C Particle Image Velocimetry (PIV) were carried out and reported concerning the flow field past a generic car body (modified Ahmed body) which is equipped with wheels and wheel-arches. The Reynolds number was chosen to not exceed 2E+5 based on the height of the Ahmed body which makes it possible to investigate the same configuration by means of Large Eddy Simulation (LES). The wheels were rotating but the ground was stationary. The wheel-ground contact was realized by means of small rectangular openings below the wheels in the ground plane in which the wheels were immersed. The transition contour of the immersed wheels and the ground, as well as the rectangular openings below the wheels were properly sealed to prevent parasite flow and to provide well defined boundary conditions for an upcoming LES investigation.

The flow field was measured in several planes with normal vectors pointing towards the directions normal to the free stream. Statistical characteristics of the flow are provided and discussed.

1. Introduction

The aerodynamic effects of the rotating wheels on road vehicles are a topic of high importance in vehicle aerodynamics. Wheels on vehicles have high impact on both lift and drag coefficients. According to several studies (see e.g. Eloffson and Bannister, 2002; Waschle, 2007; Skea et al., 2000) the presence of wheels and wheel-arches on an aerodynamically optimized passenger car body increases drag and lift by an amount of 30% and 40%, respectively. Due to their functionality, wheels cannot have an aerodynamically favourable shape.

During the last couple of decades, several publications discussed the characteristics of the flow field past isolated wheels (Fackrell et al. (1973); Mears et al., 2002; Brizzi et al., 2004), wheels in wheel-arches (Skea et al., 2000; Fabijanic, 1996; Axon et al., 1999; Cogotti, 1983) and full cars (Eloffson and Bannister, 2002; Waschle, 2007) both on experimental way as well, as by Computational Fluid Dynamics (CFD). In case of wheels rotating in wheel-arches the investigated geometry was either complicated (Cogotti, 1983), not completely representing the case of a conventional car (Skea et al., 2000; Axon et al., 1999) or its details were not open for public access (Waschle, 2007; Axon et al., 1999).

The intention of the present research is to provide reference data for a car model that has known, simple geometry and is equipped with four wheels rotating in their wheel-arches. The choice of the authors of this paper was made on the well known Ahmed body due to its well documented, simple geometry. The modified Ahmed body was already investigated by means of Reynolds-Averaged Navier-Stokes (RANS) modelling in Regert et al. (2007). The differences of the flow field characteristics between the Ahmed body and the modified Ahmed body, based on RANS modelling, were discussed in Regert et al. (2007). To further improve the reliability of the computational results, the need for experimental results arose for the purpose of validation.

It is well known in the research community of bluff bodies (e.g. Krajnović and Davidson, 2005a, 2005b; Schmidt and Thiele, 2002; Rodi, 1997; Craft et al., 2002) that, in spite of its excellent performance in determining the forces acting on bodies, RANS modelling fails when the structure of the flow field is to be analyzed (Krajnović and Davidson 2005a, 2005b; Craft et al., 2002). The only reliable and affordable approach to obtain information concerning the structure of the flow field is Large Eddy Simulation (Krajnović and Davidson 2005a, 2005b). However, LES requires more and
more computational efforts with increasing Reynolds number due to the wide range of appearing vortical structures to be resolved. For this reason the experiments were designed for a maximum Reynolds number of $2 \times 10^5$ based on the height of the Ahmed body. Although this Reynolds number is not representative for full scale vehicles, it can serve as a validation case for LES computations.

In the scope of experimental investigations up to now, the applied measurement techniques were force and surface pressure distribution measurements (Skea et al., 2000; Fabijanic, 1996; Axon et al., 1999; Cogotti, 1983) and Laser Doppler Velocimetry (LDV) (Waschle, 2007). PIV experiments were already carried out and published for the case of isolated rotating wheel in Brizzi et al. (2004). To the authors’ knowledge, PIV experiments regarding to the flow past a vehicle with wheels and wheel-arches has not been published for research purposes. The Ahmed body with wheels provides a configuration that is open for the public in all its details. The present experiments represent the first step for the determination of the flow field past a realistic, non-confidential road-vehicle configuration. The experimental results help in understanding the main flow features past the wheels and the interaction of the flow past the vehicle and the wheels, on one hand. On the other hand the present experiments targets to provide a database for the validation of numerical simulation results that would lead to an even deeper understanding of the flow features and the mechanisms that lead to such a high increase in both lift and drag due to the presence of wheels. Although the present paper shows only a small fraction of the experimental results, the experiment campaign is in progress to provide a full map of the flow field. Here, the authors concentrate mostly on the description of the experiments and the flow past the front wheel is discussed.

The structure of this paper is the following: in the second section the geometry of the generic car body with wheels is shown in detail. The wind tunnel model and its accuracy is also discussed along with the configuration of the test section. The third section discusses the PIV system setup and the measurement locations illustrating the location of the laser and camera devices. In the fourth section the uncertainty of the results are discussed. The fifth section discusses the measurement locations and configurations and finally the sixth section shows the mean flow field based on the velocity vector fields.

2. The wind tunnel model

2.1. The generic car body with wheels

The Ahmed-body equipped with wheels was first published by Regert et al. (2007), but for the sake of clarity, its structure and dimensions are provided here. As a reference, the Ahmed body with the slant angle of $25^\circ$ was chosen. The wheels were designed to maintain the same under body gap as for the original Ahmed body. The geometry of the wheel arches was a half cylinder with a small flat extension downwards. Its diameter and depth was tuned to mimic the proportions usually found on road vehicles. The geometry of the vehicle and the sizes are shown in Fig. 1 according to the original setup used by Ahmed et al. (1984) and Lienhart and Becker (2003). The sizes of the Ahmed-body are expressed in terms of its height, $H$ and the wheel diameter $d$ ($H = 215$ mm and $d = 108$ mm for the present case). The geometrical axles of the cylinders modelling the wheel arches of the vehicle were placed in the same location as that of the wheels. The outer vertical surfaces of the wheels were aligned with the side plane of the vehicle model. The wheel axles are cylinders.

Fig. 1. Geometry of the modified generic car body with wheels and wheel arches.

Fig. 2. Top: Wind tunnel model of the generic car body with wheels. Bottom: Interior structure of the generic car body with wheels (top surface removed).
The wind tunnel model and its interior structure can be seen in Fig. 2. The vehicle body was built up onto a frame constructed by using commercially available aluminium profiled rods that are fixed to each other by bolts. The two sidewalls of the vehicle are made of 11 mm thick poly-ethylene sheets. The top face, the slanted surface, the base and the under body of the vehicle were made of aluminium sheets of 2 mm thickness and bolted to the 11 mm thick faces of the sidewalls. The rounded front face was made of fibre-glass composite material and it is a single piece structure. The model was designed to hang from a strut, thus providing the possibility for rotating wheels with stationary ground. This configuration is not relevant in practice, but well suitable for validation of computational fluid dynamics (Krajnović, 2010). The connector disk can also be well visible in Fig. 2. The wheel pairs (front wheel pair and rear wheel pair) were connected to an axle. Each axle was equipped with two deep-groove roller bearings. The casings of the bearings were fixed to the main aluminium frame of the model. Inside the vehicle model, a single-phase AC electric motor was placed and drove the two axles simultaneously by means of ribbed belt drive. This solution ensured that both the wheel pairs rotated at the same rpm. The rotation speed was measured by an optical counter device that was also fixed inside the model and watched a marker on the front axle. The signal of the optical counter was transformed into rpm by a digital counter. The single phase engine was regulated by a toroid transformer. 

To prevent the propagation of any vibration originating at the engine due to any imperfections of the engine and the connecting elements, the engine mounting points were isolated by rubber sheets. The axle of the engine was connected to the axles of the wheels by means of ribbed belts that also helped the damping of any spurious vibration and ensured the drive of wheels without any slip w.r.t. the engine rpm. During the tests, no detectable vibration occurred at the rotation of wheels. The wheels were made of poly-ethylene blocks and were also equilibrated to avoid their vibration on the axles. During the tests there was no detectable vibration observed.

Cables of the engine and the rpm measuring device were guided out from the model inside the strut system, thus they were hidden from the flow. The wheel axles crossed the vertical surface of the wheel-arch through a sealed bore that had a physical contact with the axle. This structure prevented any flow leakage between the interior and exterior of the model. The engine was sufficiently powerful to keep the required rpm also in case of having sealing parts that touched the rotating elements.

After mounting the top, slanted face, base, underbody and front face elements to the main side walls of the model, model clay was used to fill all eventual gaps. The geometry parameters were fine-tuned when the model was assembled. After filling the micro-gaps and the heads of bolts, some layers of two-component filler material were sprayed onto the surface. After a second fine-tuning of the sizes of the model, the surface was polished and painted mat black to accommodate for PIV measurements.

The rotation of the wheels was solved by having no contact with the ground. However, due to the problems in CFD when meshing the wheel-ground contact, it has been chosen to realize a similar structure for the wind tunnel model, too. Four rectangular openings slightly larger than the ground contact patch of the wheel when immersed 3 mm (0.027d where d is the wheel diameter) were formed in the ground plane. Each rectangular opening was filled by a piece of textile with 5 mm long impermeably dense fur. The fur has filled all the depth of the rectangular opening up to the plane of the ground. For final tailoring and to ensure the integrity of the ground plane surface, thin tape was used to cover the rectangular opening on the top. The tapes were tailored to fit the “simulated” ground-contact contour of the wheels and there was a physical contact between the rotating wheel and the tape contours. This way any possibility for leakage was closed out. The tapes were approximately 0.1 mm thick and were fixed onto the ground plane. The authors expected negligible effect of this small roughness on the already turbulent boundary layer along the flat ground plane.

2.2. Wind tunnel reference frame

For the discussion of the experimental results it is necessary to define the coordinate system applied for the present setup which is indicated in Fig. 1. X denotes the direction of the free stream on the way that the X axis is pointing in the downstream direction. Y denotes the lateral or span-wise direction. Z denotes the direction normal to the ground plane, pointing upwards. X, Y, and Z are forming a right-handed Cartesian coordinate system. In the paper the authors use also the term “top view” for denoting the view of the laser sheets having their normal vector pointing towards the Z axis. In this case the camera axis coincides with the Z axis. The other term used in the paper is the “side view” which indicates the case when the laser sheets have their normal vectors aligned with the Y axis. In this case the camera axis is aligned with the Y axis. Due to the limitations of the camera there were no images taken on the planes with normal vectors pointing to the direction of the X axis.

2.3. Test section configuration

The overall configuration of the test section can be seen in Fig. 3. The nozzle outlet diameter of the Göttingen type wind tunnel is 2.6 m (for further details of this wind tunnel, see Karman WTL, 2012) and the blockage of the vehicle model including the struts and the ground plane construction was computed to be 2.5%. The vehicle model is hanging on a strut system. There is a horizontal strut spanning over the test section with both of its ends being

![Fig. 3. Wind tunnel test section configuration for the PIV experiments. Y-normal plane recording configuration with Laser head in the jet downstream the model.](image)

![Fig. 4. The profile of the leading edge of the ground plane. Flow from right to left.](image)
outside the jet of the wind tunnel. Outside the jet of the test section the horizontal strut is fixed to two vertical steel bars of square cross section. The fixing parts permit the fine adjustments of the “riding height” of the model, which provides a method for immersing the wheels precisely by 3 mm into the openings in the ground plane.

The horizontal strut is a steel bar of square cross section which is covered by a NACA 0015 airfoil envelope with a chord length of 300 mm. In the mid-span of the horizontal strut, a circular cross section steel bar is mounted vertically that holds the vehicle model itself. The vertical strut is also covered by a NACA 0015 airfoil with a chord length of 170 mm. The airfoils were made of glass-fibre composite material and their geometrical accuracy is 0.1 mm. The junction between the two airfoils is the simple perpendicular transition contour between them without any fillet, any additional treatment to make it easy to model by CAD and to mesh for CFD.

On the other end of the vertical strut, the airfoil ends simply in the plane of the vehicle's top surface. Here also sharp corners are created to avoid any fillets for providing precise boundary conditions for CFD. It can be also observed that there is a gap between the connector disk and the top face of the vehicle model. It was designed for force measurements but for now, it was filled by model clay for the PIV measurements.

The ground plane was a raw wooden sheet without any polishing treatment on its surface to ensure the development of a turbulent boundary layer with early transition. The ground plane was shifted downwards in flow-normal direction with respect to the centre of the wind tunnel outlet nozzle. The leading edge of the ground plane had to be inclined downwards to ensure attached flow. The leading edge has been made of aluminium sheets that were bent by a radius of 3 mm. A section of them can be seen in Fig. 4. At the inclination region there is a jump in the curvature that promotes transition but does not lead to detectable separation bubble. Due to this special geometry of the leading edge, the authors decided to measure the inlet velocity profiles in detail at multiple span-wise locations (not reported here).
3. PIV measurement system

Measurements have been carried out by a non-time-resolved 2D–2C PIV system. The system was distributed by ILA GmbH and consisted of a Solo Nd:YAG laser from New Wave Technology that produces laser pulses with an energy of 15 mJ and 3–5 ns duration with a repeatability frequency of 15 Hz for each cavity. For recording the images, a PCO Pixelfly double shot CCD camera was used. The synchronization was solved by the compact system provided by ILA GmbH. The laser was equipped with a cylindrical lens unit providing a laser sheet. The minimum separation time used during the experiments was 200 \( \mu \)s that was accommodated for the low Reynolds number flow. This time separation produces approximately a maximum particle displacement of 10 pixels (approximately 1 mm for the current magnification) at the high velocity regions for a domain of physical sizes 130 mm \( \times \) 100 mm. To capture the images, a Nikon 50 mm objective was used on the camera. The 50 mm objective was set to f# of 11 to produce a depth of field of 20 mm which was sufficient to ensure minimal focus settings regarding all the laser sheet positions (three consecutive planes were in focus).

The seeding was provided by using olive oil droplets generated by a commercially available device: TSI 9307-6 six-jet oil droplet generator that produces droplets with diameters of approximately 1 \( \mu \)m. The seeding was injected downstream of the test section into the collector of the wind tunnel. It has passed along the recirculation pipe, through the fan and all turbulence decreasing screens before entering the test section from the inlet nozzle. Thanks to the recirculation of the air in the Göttingen type wind tunnel, sufficient amount of seeding droplets persisted in the wind tunnel for the duration of data acquisition for a given laser sheet position. The seeding density was 4.3 particles/mm\(^2\) on the images. This density provided at least 8 particles in the smallest interrogation area (16 \( \times \) 16 pixels). This particle density is sufficient for the correlation of sufficiently good quality.

To characterize the flow field past the generic car body, several laser sheet positions were used and 300 image-pairs were collected for each sheet position.

Fig. 6 (continued)
When Z-normal planes were recorded, the laser head was mounted onto a 3D electronic traversing system that provided an accuracy of 0.1 mm. The traversing system and the laser were outside the jet of the wind tunnel when Z-normal planes were recorded. The laser sheet generating optics was a small C-mount type compact unit that was fixed on the outlet port of the beam. This way the laser sheet producing optical element was moving together with the head.

To provide the required field of view for the Z-normal planes by using the 50 mm Nikon objective, the camera had to be placed into the flow field in the vicinity of the horizontal part of the strut holding the vehicle model. As the Reynolds number was very low and forces were rather weak, the flow did not exert sensible effects on the camera itself, however, it lead to a risk for the modification of the flow field in the vicinity of the vehicle. The effect of the vicinity of the camera was investigated by observing the flow in the vertical laser sheets with and without the presence of the camera in the flow. The camera was modelled by a wooden block of similar geometry, mounted on the camera holding strut. The results showed that there was no sensible effect of the presence of the camera on the flow field past the vehicle.

In case of the second configuration when the planes normal to the Y direction were recorded the laser head had to be installed inside the wind tunnel jet, downstream the Ahmed body (as opposed to the Z-normal plane configuration when the laser was outside the wind tunnel). As the distance of the laser head was 3.2 vehicle lengths from the base of the vehicle, the authors expected backward effect. To investigate the amount of this effect, a sensitivity study has been carried out by varying the distance of the laser from the vehicle and recording image pairs at several locations in the wake of the vehicle. Based on the measurement results, there was no sensible effect of the presence of the laser head on the flow field characteristics.

The axis of the camera lens was mostly perpendicular to the laser sheet, but to ensure the planar measurements, the mapping utility of the VidPIV software (ILA) was applied to de-warp the images to get rid of perspective effects.

The authors have chosen to apply the software WiDIM (Window Deformation Iterative Multigrid) Scarano and Riethmüller (2000) to determine the velocity vector fields with the kind permission of the von Karman Institute for Fluid Dynamics, Rhode-Saint-Genese, Belgium, which was found to perform more satisfactory than VidPIV for the present case. The image pairs were processed by an initial window size of 64 × 64 pixels with two interrogation window refinements (16 × 16 pixels final window size) and 75% overlapping was imposed to obtain one vector by 4 pixels (for PIV terminology, see e.g. Scarano and Riethmüller 2000). This means one vector by 0.35 mm.

4. Uncertainty analysis

The uncertainty analysis covers the discussion of errors originating from the vehicle model, the wind tunnel, the PIV measurement configuration and the determination of displacement field.
4.1. Vehicle model and wind tunnel

The vehicle model consists of several separate parts bolted together by using immersed-head bolts. To achieve the most precise sizes, the interior main frame was tailored carefully. The aluminium sheets had an error less than 0.1 mm regarding their thickness distribution. The poly-ethylene side walls were less accurate thus adjustments at the interior side of them were realized to maintain constant width of the vehicle along its length. The bolts were tightened to a limit where the aluminium sheets were not yet deformed at all. After the extensive surface treatment and finishing, the inaccuracy in size remained below 0.5 mm in general. It means that for the vehicle sizes the error of the geometry is 0.2% of the vehicle height \( H \), while for the wheels the same error results in 0.46% of the wheel diameter \( d \).

The airfoil contours on the struts had an error of 0.1 mm which means an error of 0.06% of the smaller (170 mm) chord length for the vertical strut and 0.03% for the bigger (300 mm) chord length on the horizontal strut.

Measurements were carried out for 5 m/s free-stream velocity that corresponds to a Reynolds number of \( 7.17 \times 10^4 \). With the present diameter of the wheel the rotation frequency was set to 15 Hz (the exact value is 14.74 Hz). The smallest digit on the rotation frequency indicator was 1 Hz, thus the error of the rotation speed of the wheels was maximum 6.7% of the target value.

The wind tunnel is driven by a DC electric motor and regularized by sliding resistances. Throughout the measurements, the rpm of the wind tunnel fan was set to produce the same total pressure upstream the convergent channel of the nozzle. The pressure was measured with an accuracy of 1 Pa that leads to a maximum of 3% error in the measurement of the free stream velocity (5 m/s).

4.2. PIV processing

The uncertainty of the PIV measurements originates from the quality of the images, the accuracy of the software to determine the displacement field and the properties of the statistical analysis carried out on the results.

The laser sheet was adjusted by turning the cylindrical lens head mounted onto the laser head. The horizontal reference plane was the ground itself. A sheet of paper with a calibration pattern of minimum feature size of 1 mm was used. Two other alignment references were: the imaginary line connecting the centres of the front and the rear wheel on one side; the top surface of the vehicle. The laser sheet thickness was approximately 1 mm and the length of the reflection stripe that was used for monitoring horizontality was 200 mm taking into account an error of the adjusting as 1 mm at both ends of the laser sheet, the maximum alignment uncertainty is estimated to be 0.57°. The horizontality in the span-wise direction was set on a similar way, but with a calibration plate slightly inclined about the normal direction of the ground plane. In this direction the length of the reflection stripe was 300 mm, yielding a maximum error of 0.38° for the alignment.

The next source of error is the misalignment between the camera CCD plane and the laser sheet. This error was automatically
compensated by the VidPIV software of ILA by using its built-in mapping utility. The mapping is based on marking the four corners of a rectangle on a calibration image and providing the true size of each side. Images are then warped into the plane of the CCD sensor of the camera based on the four corners and the corresponding true sizes.

The magnification of the camera provided particle image sizes of minimum 3 pixels, permitting a good basis for Gaussian fitting for sub-pixel precision and to avoid peak-locking.

For the laser sheet positions reported here, the quality of image pairs ensured that the signal to noise ratio was higher than the limit of 2.3 for 91% of the velocity field for each time instant in case of Z-normal planes, based on the statistic information of the WiDIM software (Scarano and Riethmuller, 2000). One problematic region was found beside the front half of the wheel. Here the signal to noise ratio was approximately 1.3 due to strongly 3D flow. The determined displacements were expected to be loaded with higher errors. The Z-normal planes (top view) are patched up from two halves: front and rear part of the zone near the wheel. Due to this problematic region one can observe some slight discontinuities at the overlapping regions in this area next to the wheel. The side view configuration suffers from worse signal to noise ratio due to the perturbing effect of the background even after background subtraction for the planes that were closer to the side of the vehicle than 10 mm (0.092d). In the results shown in this paper, the regions where the signal to noise ratio is below the acceptable limit, are not represented.

The accuracy of the magnitude of the displacement vectors determined by using WiDIM Scarano and Riethmuller (2000) has been reported to be 0.1 pixel. On the physical scale, on average, 1 mm = 10 pixel was determined, yielding a displacement error of 0.01 mm. The accuracy of the separation time has been found to be approximately 1 μs. By using these two errors, the absolute error of the velocity for the case of 10 pixels displacement of the particle images is estimated to be 0.06 m/s based on the quadratic propagation of errors.

Mainly due to the strong temporal limitations for the research facilities, 300 image pairs were recorded for each laser sheet positions. Being the time realizations uncorrelated with each other and assuming Gaussian distribution of the velocities around the mean value, a simple statistical method was applicable for the estimation of the error of the mean and RMS velocities. The maximum error in the mean quantities is 5% of the free stream velocity (where the maximum error was found at the location where the RMS of velocity reached 20% of the free stream velocity).

5. Measurement locations and conditions

Measurements were carried out in several laser sheet positions in the vicinity of the front wheel, the rear wheel, the wake, the slanted surface and upstream the body, but in this paper only the front wheel region is discussed. The locations discussed in this paper are indicated in Fig. 5.

The results of the measurements are shown for the region beside the rotating front wheel in 9 planes oriented with the normal vector of the ground plane, i.e. the Z axis of the reference frame. These planes are referred as ‘top view’ during this discussion as mentioned in Subsection 2.2. These measurement planes are
recorded in two halves to include the upstream and downstream regions in the vicinity of the wheel. For the discussion of the results the two halves are merged into one single image by using Tecplot software.

Another set of 11 planes are shown with their normal vectors oriented in the Y axis direction. These planes are called ‘side view’ in this paper. These planes were recorded in a single field of view.

The represented planes have been chosen as follows: the reference plane of the top view is crossing the centre of the wheel, so it represents position 0.0d, positive direction is defined as the direction in which the distance between the ground plane and the measurement plane increases. The positions of the planes are at the following distance from the centre of the wheel: −0.277d, −0.185d, −0.0925d, 0.0d, 0.185d, 0.278d, 0.37d, 0.556d, 0.648d. The horizontal planes that represent a top view of the flow are covering the total height of the wheel arch. The side view planes are located at the following horizontal distances from the side of the vehicle: 0.138d, 0.184d, 0.23d, 0.277d, 0.323d, 0.369d, 0.416d, 0.462, 0.508d, 0.555d, 0.6d.

The inlet velocity field has been recorded in three planes: one plane was coincident with the symmetry plane of the vehicle body and it covers the region from the leading edge until the front face of the body. Two planes were recorded between the middle plane of the vehicle and the left edge of the ground plane. The first plane was 0.814H, the second plane 3.837H from the middle plane of the vehicle.

The measurement data is available for the public via communication to the corresponding author.

The free stream velocity is set to 5 m/s for all measurements. The results that are reported here correspond to rotating wheels.

### 6. Results

The top view of the contours of velocity magnitude and the streamlines of the flow field can be seen in Fig. 6.

The flow arrives at a velocity of 5 m/s at the vehicle and as it turns around the leading edges of its front face, it accelerates up to a maximum of 6.7 m/s along the sides. Due to the discontinuity in the curvature of the junction between the rounded leading edge and the flat side face of the vehicle, the boundary layer separates and forms a small separation bubble. The flow thus deflects slightly away from the surface of the vehicle upstream the front wheel. This can be observed in Fig. 6 on plane 0.0d which is the reference plane. The flow then becomes parallel to the side surface of the vehicle.

Positioning the laser sheet in locations above the centreline of the wheel, one can see that the streamlines are getting more and more deflected from the surface in the region besides the side opening of the wheel arch. This is due to the flow coming outwards over the top half of the wheel. The maximum amount of outflow is located approximately at 0.556d and 0.648d between the top of the wheel and the highest point of the wheel arch curve. This flow structure has been already visualized experimentally by Fabijanic (1996), Merker and Berneburg (1992), Oswald and Browne (1981), and by means of RANS modelling by e.g. Regert and Lajos (2007) and Regert et al. (2007).

In the region next to the wheel surface but above its centre, the streamlines become well aligned with the side face of the vehicle, even with that of the wheel. This suggests that there is no in- and outflow to and from the side opening of the wheel arch upstream and downstream the wheel between the wheel surface and the wheel arch in this region.

![Fig. 8. Streamlines with the contours of Turbulence intensity related to the freestream velocity for horizontal planes (top view) beside the front wheel region. From top to bottom the planes are: 0.648d, 0.556d, 0.37d, 0.278d, 0.185d, 0.0d, −0.0925d, −0.185d, −0.277d measured from the center of the wheel. Flow from left to right. Contour code and indication of axes on the top image.](image-url)
Above the centre of the wheel, at 0.185d and 0.37d it can be seen that the streamlines are turning towards the side of the vehicle in the vicinity of the wheel. This reversion in the direction of streamlines indicates that the top of the longitudinal vortex is reached.

In the plain aligned with the centre of the wheel it can be seen that there is a cross flow upstream the wheel coming out from the wheel arch. There is no separation directly visible on the outer side of the wheel, however the flow is three dimensional here due to the rotation of the wheel, the flow mainly follows the rounding of the wheel shoulders and attaches to its side face. Along and downstream the wheel the flow slows down, indicating that the cross flow originating from upstream the wheel at its central plane leads to a loss of stream-wise momentum of the main flow.

Moving with the laser sheet from the centre of the wheel towards the ground plane it can be seen that there is a reasonable outward deflection of the streamlines away from the side surface of the wheel. This is most probably related to the significant contribution of viscous effects at this low Reynolds number.

The wheel rotation manifests its most visible effect at the lower part of the wheel. At a distance of −0.277d below the centreline of the wheel a vortex can be observed which is rotating into the opposite direction of the well known dominating longitudinal vortex originating from the “jetting” effect described first by Fackrell et al. (1973). This vortex is related to the presence of the stationary ground plane next to the rotating wheel. Similar phenomenon was already observed in Schiefer (1993) where an isolated wheel was rotating on a stationary ground plane. In case of moving ground plane and rotating wheel this vortex is not attaching onto the ground.

Downstream the wheel the wake extends to a significant width. The streamlines seem to indicate a flow moving sideways with a slight forward pointing component. This indicates the presence of a longitudinal vortex along the lower part of the wheel which is most probably identical to the large longitudinal vortices observed in several studies (Waschle, 2007, Fabijanic, 1996, Regert and Lajos, 2007). It can be also seen that the flow approaching the wheel is already characterized by a significant yaw angle. This
is a well known phenomenon that occurs due to the depression on the rounded surfaces of the two side leading edges. The significant yaw angle is occurring only at the front wheels. The rear wheels of the vehicle are exposed to an almost zero yaw angle flow. This yaw angle for the front wheels is the reason for the large widening of the wake of the front wheel downstream along the side of the vehicle.

The side view of the flow field is represented on the images in Fig. 7. The closest position to the side of the wheel is \( 0.138d \). Here one can observe that the flow is arriving in the region next to the wheel with almost horizontal streamlines above-, while the streamlines are inclined upwards below the level of the centre of the wheel. In the region between the top surface of the wheel and the wheel arch the streamlines deflect significantly that is most likely related to the outflow from the wheel arch that was mentioned above. Beside the wheel one can observe a recirculation region. This region is an oblique section of the dominating longitudinal vortex. One can observe the longitudinal character of this vortex based on the fact that the streamlines are spirals and the centre is appearing more and more downstream as the laser sheet is moved away from the side surface of the vehicle. The vertical extension of the vortex reaches the height of the centre of the wheel.

The flow in general is in a good agreement with the observations of previous works (Regert et al., 2007; Fabijanic, 1996; Waschle, 2007).

The turbulence intensity which is related to the free stream velocity indicates the unsteady character of the flow. The turbulence intensity distributions are shown in Fig. 8 from top view and in Fig. 9 from side view. It can be observed that the maximum value of the turbulence intensity does not exceed 30% anywhere in the field. In Fig. 8 it can be observed that at position \( 0.648d, 0.556d \) and \( 0.37d \) above the centre of the wheel the turbulence intensity is high, which is due to the turbulent nature of the flow coming out from the wheel arch above the wheel and due to the interaction between the exiting flow and the flow coming along the side of the vehicle. The unsteadiness of the flow decreases significantly in the region between the centre and the top of the wheel. At this region also the streamlines are uniformly organized. The turbulence intensity increases in the region below the centre of the wheel. It can be observed that high values are concentrated at the boundaries of the large wake zone beside the wheel. Inside the main longitudinal vortex the turbulence intensity seems to decrease that suggests that this vortex has an inviscid-like nature in its inner region, like in case of trailing vortices of aircraft. Downstream the wheel the large longitudinal vortex is affected by turbulent mixing that leads to the increase of turbulence intensity over most of its cross section.

The side view that is represented in Fig. 9 shows that the turbulence intensity has a higher value in the shear layer of the large longitudinal vortex. Getting further from the side of the vehicle the longitudinal vortex is cut obliquely on its outer region that
explains the increase of turbulence intensity values. The turbulence intensity was influenced by the disturbing effect of the reflections occasionally appearing on the surface of the vehicle when oil droplets were depositing on it. Those parts of the results that were mostly influenced by this effect are not shown on the images.

7. Conclusions

In the present paper the measurement setup and the results of the PIV investigation of the rotating front wheel of an Ahmed body equipped with wheels and wheel arches is presented. The tests were carried out with rotating wheels and stationary ground. The contact between the ground plane and the wheels was modelled by immersing the wheels into the ground plane by 3 mm and sealing the remaining gaps. The free stream velocity was set to 5 m/s to stay below a Reynolds number of 2.0E+5 based on the height of the Ahmed body (measured from the bottom of the Ahmed body). In this paper only the front wheel is investigated by analyzing the flow field in top and side views. Similar measurements were taken for the rear wheel and in the wake of the vehicle during the measurement campaign, but these are not presented in this paper.

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References


