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Effects of an Air Spoiler on the Wake of a Road Vehicle by PIV Measurements

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Abstract : A particle image velocimetry (PIV) technique has been used to analyze the flow characteristics behind a road vehicle with/without an air spoiler attached on its trunk and also to estimate its effect on the wake. A vehicle model scaled in the ratio of 1/43 is set up in the mid-section of a closed-loop water tunnel. The Reynolds number based on the vehicle length is 10^5. To investigate the three-dimensional structure of the recirculation zone and vortices, measurements are carried out on the planes both parallel and perpendicular to the free stream, respectively. The results show significantly different vorticity distributions in the recirculation region according to the existence of the air spoiler. The focus and the saddle point, appearing in the wake, are disposed differently along the spanwise direction. Regarding the streamwise vortices, the air spoiler produces large wing tip vortices. They have opposite rotational directions to C-pillar vortices which are commonly observed in the case that an air spoiler is absent. The wing tip vortices generate the down force and as a result, they might make the vehicle more stable in driving.

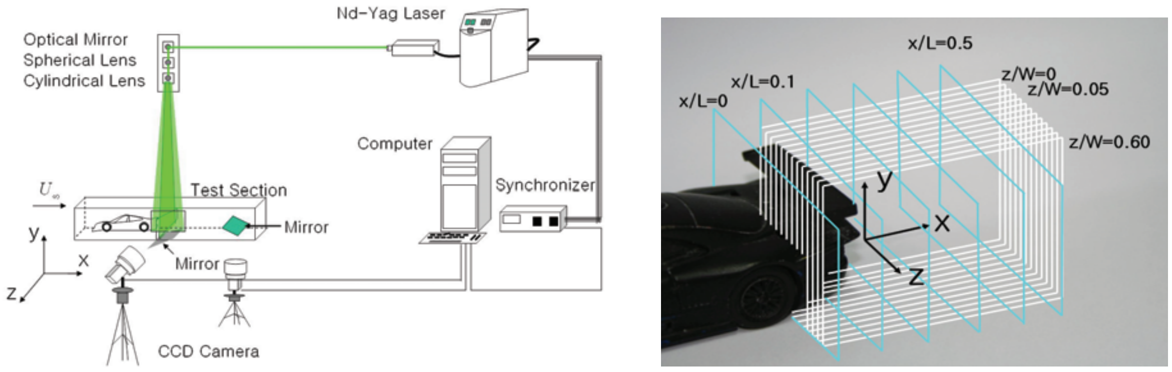
Keywords : PIV, road vehicle, Three-dimensional wake, Air spoiler, Isovorticity surface.

1. Introduction

There have been many studies to understand the wake structure behind a rear body of a road vehicle through numerical and experimental methods. The former such as large eddy simulation (LES) method can suggest the information of the three-dimensional wake structures, drag coefficients, etc (Krajnovic and Davidson, 2004; Han, 1989). However, they have still shown lots of differences from the experimental data because the complicated geometry of a road vehicle and the high Reynolds number made the results sensitive to the number of mesh and so on. On the other hand, experiments on a full-size vehicle model can provide relatively exact information of the flow field. Most of the previous experimental researches devoted to understand the overall quantities such as aerodynamic forces and wake size using the point measurement techniques such as hot wire anemometry (HWA), laser doppler velocimetry (LDA) and pitot probes (Ahmed et al., 1984; Lienhart and Becker, 2003). Some of them also visualized the flow qualitatively using tuft, smoke, or oil to supplement their results (Azim and Gawad, 2000; Gilhome et al., 2001; Jenkins, 2000; Kee et al., 2001; Landman and Koster, 2000). Even though these techniques give sufficient information about the wake properties, the three-dimensional flow structures still remain far from being fully resolved.

Recently, a quantitative visualization using PIV (particle image velocimetry) has been tried to investigate the flow field around a road vehicle. Cogotti and Gregorio (2000) studied the wake of the rear-view-mirror and the flow field around the left side of a frontal wheel of the full-size vehicle. McCutcheon et al. (2002) investigated the wake flow of the simplified car model according to the angle of the hatchback. Al-Garni and Bernal (2003) and Heineck and Walker (1999) carried out PIV measurements to examine the characteristics of the turbulent flow around a truck. However, these studies have not analyzed completely the whole wake including recirculating zone but done only a simple investigation on the flow features in the far wake. It is necessary to have a systematic approach (Gushchin et al., 2004; Calluaud et al., 2005) in the aspect of three-dimensional vortex structures because the safety as well as the fuel consumption rate in driving a road vehicle is determined to a great extent by the highly three-dimensional flow characteristics around that.

Therefore, in this study, PIV measurements are carried out for the analysis of three-dimensional vortex structure developed in the wake behind a kind of a sports car, which generally adopts an air spoiler on the trunk to increase the driving stability in a high speed regime. For the experiments, model vehicles with/without an air spoiler is set up in the water tunnel facility and the velocity fields in the wake are measured in multiple sectional planes of spanwise and streamwise directions. To investigate the effect of the air spoiler which has a negative angle of attack in the wake of a road vehicle, quasi-three-dimensional isovorticity surfaces for spanwise and streamwise vortices are evaluated on the parallel and vertical planes to the free stream. The three-dimensional reconstruction is made by simply piling up the sectional measurement data and then the spatial variations of these vortices are compared and discussed.



(a) Schematic diagram of the PIV syste (b) Measurement planes behind a road vehicle

Fig. 1. Experimental setup.

2. Experimental Setup and Scopes

Figure 1(a) shows the schematic apparatus used in this experiment. The PIV system consists of the closed-loop water tunnel, double-head Nd-Yag laser, CCD camera, synchronizer and computer for the image processing. The dimensions of the test section which is made of transparent acryl are 700(length) × 100(height) × 150(width) mm^3, respectively. The output energy of the Nd-Yag laser is 120 mJ with 532 nm wave length. The CCD camera has the resolution of 1280 × 1024 pixels. The thickness of light sheet is 1 mm or 0.9 % of the characteristic length. The mean diameter of seeding particles named Hollow Glasses Spheres is 10 μm. A model vehicle of CLK-GRT (Mercedes Benz Inc.) was painted with lusterless black color and fixed at the center of the bottom surface of the test section. The magnitude of the model vehicle scaled with 1/43 is 112.86 × 25.56 × 45.35 mm^3 (length × height × width). It is true that a moving ground system with rotating wheels might be more plausible to simulate a real driving car on the road. However, the present experiments have performed under the static arrangement because of the difficulty in setting up the moving system inside a water tunnel facility. According to Cogotti (1998), if a complete dynamic simulation (i.e. moving ground and rotating wheels) is not possible, the second best choice is a completely static simulation (i.e. no moving ground and wheels).

As shown in Fig. 1(b), a cartesian coordinate system is referenced to determine the relative measuring positions of the vehicle from the symmetric plane. Each of the x, y and z represents the axes for the direction of length (L), height (H) and width (W) of the vehicle, respectively. The origin is set at the bottom-center of the leading edge. That is, the origin of z coordinate is located at the symmetric plane of the load vehicle. For the investigation of the spanwise vortex, a total of 13 x-y planes (63 × 50 mm^2) is measured from z/W = 0 (symmetric plane) to z/W = 0.6 with the interval of z/W = 0.05. During this plane measurement, a flat rectangular mirror is attached on the outside surface of the bottom of the transparent test section at the angle of 10° to illuminate the under part of an air spoiler as shown in Fig. 1(a). Also a total of 6 y-z planes (46 × 70 mm^2) which are varied from x/L = 0 to x/L = 0.5 with the interval of x/L = 0.1, is measured to examine the streamwise vortex. When measuring the y-z plane data, the camera is aligned under the test section standing upright to get reflected images from a rectangular mirror. The mirror which has a dimension of 60 × 50 mm^2 is attached at the bottom surface of the test section with the angle of 45° to the horizontal plane at the downstream of x/L = 2.67. To examine the effect of the mirror which is set in the test section, the x-y plane measurements are executed in the both cases that the mirror is set and not. Since the locations of vortices represented by focus and saddle points are just same for the both cases, it can be assumed that the mirror does not affect the upstream area in the wake of the vehicle.

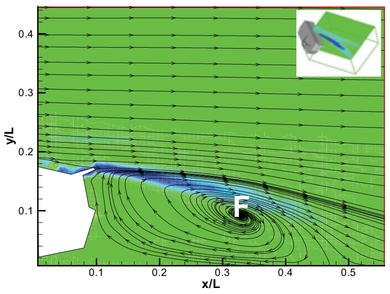
To observe the different wake flow features, two vehicle models were used; both have the same shape only except the existence of the air spoiler. At each sectional plane, 488 pairs of images were captured at a rate of 8Hz by the CCD camera in order to investigate instantaneous flow structures and the velocity data were averaged over all the instantaneous data. The focal length of the CCD camera lens is 600 mm and the each magnification factor for x-y and y-z plane measurement is 20.0 and 18.3 pixel/mm, respectively. For the vector processing, a cross-correlation algorithm (see Ref. Sung and Yoo, 2001, for more details) based on FFT is applied using interrogation windows of 32 × 32 pixels with 50 % overlapping. To enhance the signal-to-noise ratio, a window shifting and recursive correlation technique is adopted. Final spatial resolution of the velocity vectors is 1.3 and 1.1 vector/mm in the x-y and y-z planes, respectively.

3. Results and Discussion

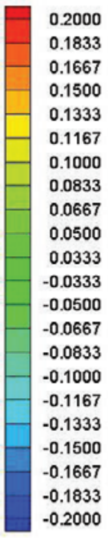
Prior to this study, the measurements in two different Reynolds numbers of 5×10^4 and 10^5 based on the vehicle length were carried out and showed that there was little difference in view of flow structure between them. Accordingly, the result will be shown just for the case that the Reynolds number is 10^5. The aim of this research is confined to observe flow structures of the wake behind a road vehicle according to whether it has an air spoiler or not.

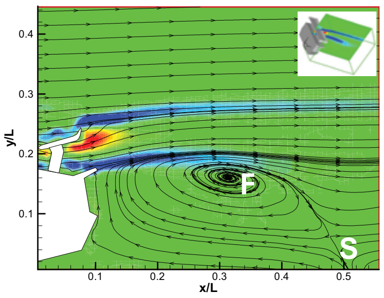
3.1 Wake Structure in the Spanwise Plane

Streamline patterns and vorticity distributions in the x-y plane are plotted in Fig. 2. It shows that the existence of the air spoiler gives the significant effect on the wake flow field. The attachment of the air spoiler which is designed to generate a negative lift in this experiment makes streamlines become larger and narrower in the direction of the height and width near the center plane of the vehicle. This phenomenon matches well with the result of Kee et al. (2001) who showed that the measured drag was improved by 3.3 % and rear axle lift was reduced by 24.8 %. Focus and saddle point appeared in the extent of z/W = 0.25 from symmetric plane when the air spoiler is equipped. However, they are observed as far as z/W = 0.3 in the case of no air spoiler. Furthermore, the position of focus is hardly changed in the height direction near y/L = 0.1 and saddle point near the bottom surface get closer to the focus as the measurement plane goes outside from symmetric plane.

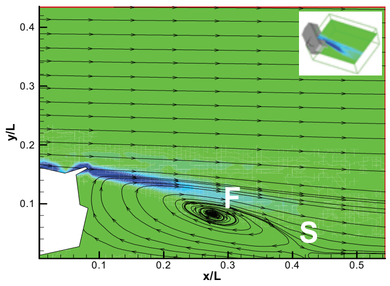


(a) z/W = 0 (without air spoiler)

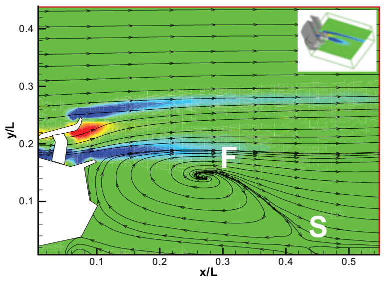




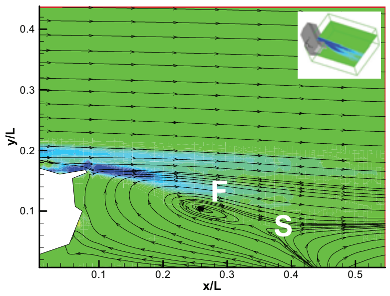
(b) z/W = 0 (with air spoiler)



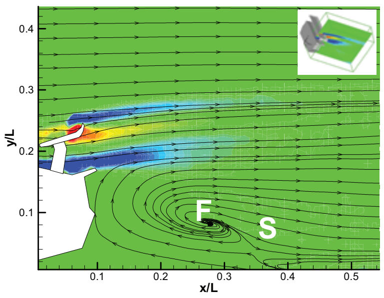
(c) z/W = 0.2 (without air spoiler)



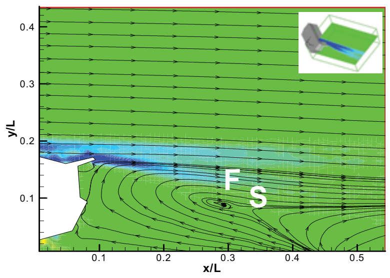
(d) z/W = 0.2 (with air spoiler)



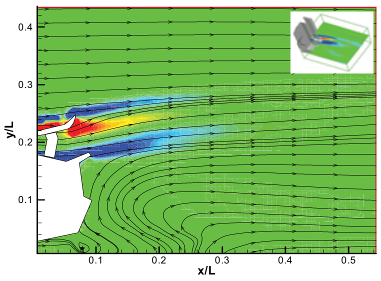
(e) z/W = 0.25 (without air spoiler)



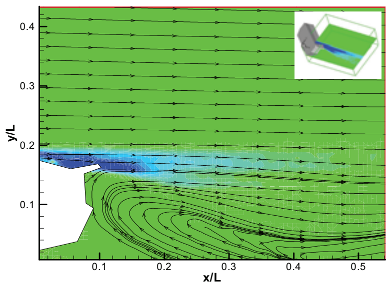
(f) z/W = 0.25 (with air spoiler)



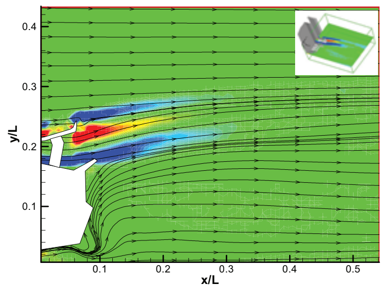
(g) z/W = 0.3 (without air spoiler)



(h) z/W = 0.3 (with air spoiler)



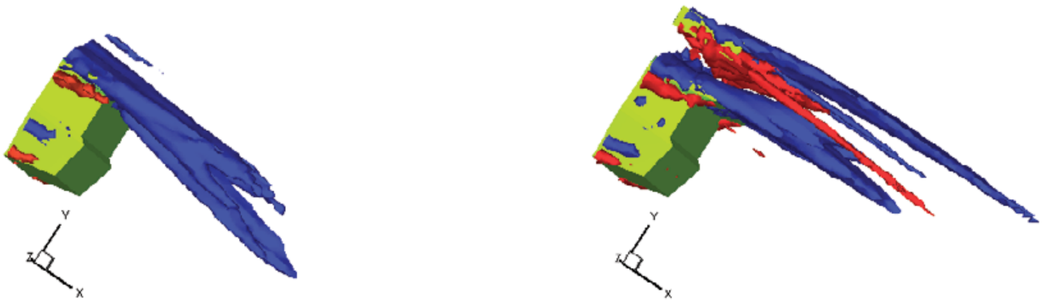
(i) z/W = 0.35 (without air spoiler)



(j) z/W = 0.35 (with air spoiler)

Fig. 2. Streamline patterns and vorticity distributions in the x-y plane. The characters “F” and “S” denote the positions of focus and saddle, respectively.

The strong reverse flow was generated at the position of $z/W = 0.35$ due to the focus merged with the saddle point. On the other hand, the air spoiler makes the focus go downward with little change in the x-direction as it moves toward outside from the center plane, and the saddle point go upstream. Therefore, it is conceived that the existence of the air spoiler improves the driving stability as a whole with minimizing the reverse flow at the bottom lateral side.



(a) Without air spoiler (b) With air spoiler

Fig. 3. Isovorticity surfaces obtained from the three-dimensional reconstruction of the spanwise vortices in the x-y plane.

Figure 3 shows the three-dimensional isovorticity surfaces whose values are ±0.1 s^{-1}. They are reconstructed from the spanwise vortex observed on the x-y plane for the two cases, that is, with and without the air spoiler. The negative vortex is generated due to strong shear flow from just above the trunk in the case of no air spoiler. On the contrary, in the case of air spoiler, a positive vortex iss formed in just behind the air spoiler, and two negative vortices, which are long and thin in shape due to strong shear flow through the space between the trunk and the air spoiler, are captured just above and below the positive vortex.

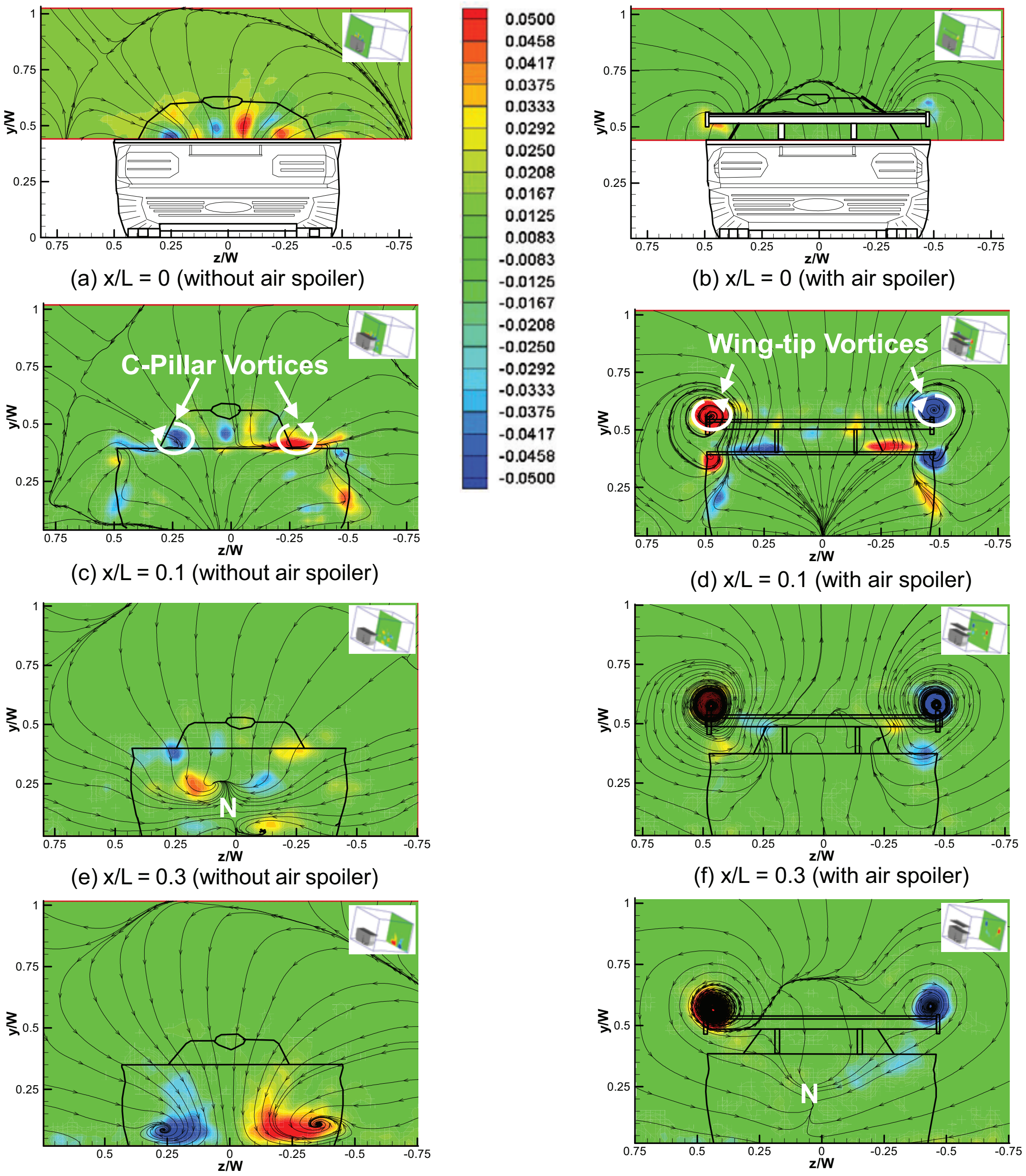
3.2 Wake Structure in the Streamwise Plane

Streamline patterns and vorticity distributions on the y-z plane are depicted in Fig. 4. A little bit unsymmetricity is stemmed from the difficulties in precise adjustment of the angles of the camera and mirror as well as a little bit imperfect alignment of a road vehicle on the bottom surface. Nevertheless, it is not so severe as much as the flow pattern is misunderstood. C-pillar vortices, which are the most representative streamwise trailing vortices in the wake of a notchback vehicle, separate at the top side of rear-glass and travel downstream along the top surface of trunk(Gilhome et al., 2001). Their paths draw concave lines and thus they appear near the center just behind a vehicle making a pair as shown in Fig. 4(c).

The present study is focused on the development of the streamwise vortices and interaction with the recirculating flow in the near wake by comparing the flow structure between the two cases, with and without the air spoiler. In the absence of air spoiler, the C-pillar vortices become a strong vortex pair due to the entraining flow from the outside into the recirculation zone as moving toward downstream as depicted in Fig. 4(g). From the streamline distribution, it is apparent that the entraining flow exists in the form of a large half circle and the boundary enlarges gradually when flow goes downstream. Node is located at $x/L = 0.3$ as plotted in Fig. 4(e), and it stays just below the focus of the spanwise vortex in Fig. 2(a). This means that there is a strong inward flow from lateral side of the vehicle. McCutcheon et al. (2002) found this phenomenon at the location of $x/L = 1.0$ but it is shown at $x/L = 0.5$ in this experiment. The discrepancy mainly results from the fact they measured the wake for a hatch-back vehicle which has different rear shape from the present notch-back vehicle. Thus, it supports well the present analysis of the developing vortices in the near wake.

When the air spoiler is adopted, the strong streamwise vortices exist to the far wake from the air spoiler. This is quite similar to a pair of the trailing vortices which are generated at the wing tips of an airplane. The only difference between them is that it has opposite rotational direction due to the overturned air spoiler. This proves reversely that the angle of attack of the air spoiler is negative.

The C-pillar vortices are also observed in the wake but do not severely affect the wake because they are weakened by the wing tip vortices which are located over the C-pillar vortices and much stronger with an opposite rotational direction to the C-pillar vortices. As a consequence, the strong wing tip vortices play an important role to make outside fluid entrain into the node at the far wake as shown Fig. 4(h). Note that the node in the streamwise plane, as shown in Fig. 4(h), is formed at the similar location with the saddle point of the spanwise vortex as in Fig. 2(b). Accordingly, the presence of an air spoiler could be linked to the fact that it generates a negative lift force by forming the strong wing tip vortices which weaken the downwash and C-pillar vortices which are the cause of increasing lift force (Kee et al., 2001).



(a) x/L = 0 (without air spoiler)

(b) x/L = 0 (with air spoiler)

(c) x/L = 0.1 (without air spoiler)

(d) x/L = 0.1 (with air spoiler)

(e) x/L = 0.3 (without air spoiler)

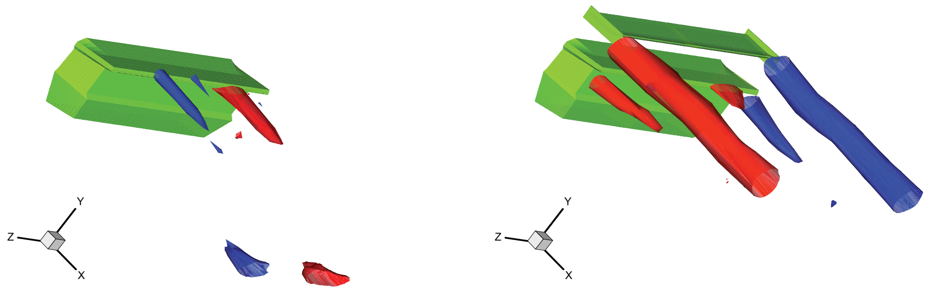
(f) x/L = 0.3 (with air spoiler)

(g) x/L = 0.5 (without air spoiler)

(h) x/L = 0.5 (with air spoiler)

Fig. 4. Streamline patterns and vorticity distribution in the y-z plane. (The characters “N” denotes the position of node.)

The two-dimensional flow field data from x/L = 0.1 to 0.5 were reconstructed into the isovorticity surface whose values are ±0.03 s^{-1} in Fig. 5. The C-pillar vortices which were generated on the trunk developed into bigger and stronger ones with entraining flow from outside in the case of no air spoiler. When the air spoiler was equipped on the trunk as shown in Fig. 5(b), the C-pillar vortices were scarcely seen but the wing tip vortices generated from the air spoiler were dominant in the wake. Thus, it can be conceived that the air spoiler improves a driving stability especially in the high-speed regime. This is primary reason to adopt an air spoiler on the road vehicle to secure the driving safety as generating a negative lift.



(a) Without air spoiler (b) With air spoiler

Fig. 5. Isovorticity surfaces obtained from the three-dimensional reconstruction of the streamwise vortices in the y-z plane.

4. Conclusions

With the PIV measurement technique, experiments have been carried out to visualize complicated three-dimensional vortex motions and to examine the effect of an air spoiler on the wake of the road vehicle at the Reynolds number of 10^5.

The recirculation zone formed larger in the height direction near the symmetric plane and narrower to the width one. The movements of the focus and the saddle point showed different patterns from each other. The one goes downward and while the other moves upstream as the flow field is observed toward outside from the center plane of the vehicle.

The streamwise wing tip vortices induced by an air spoiler have opposite rotational direction to the C-pillar vortices. These wing tip vortices are an important factor to the generation of a negative lift by weakening the C-pillar vortices, which results in enhancement of driving stability. Also, there found an interesting feature that node of the streamwise vortices prevents strong reverse flow of the spanwise vortex from being formed in the lateral side because it stays near the location of the saddle point of the spanwise vortex.

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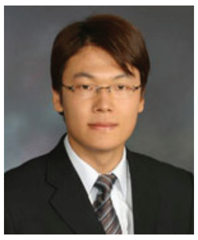

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