Research on Aerodynamic Drag Reduction by Vortex Generators

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Abstract

One of the main causes of aerodynamic drag for sedan vehicles is the separation of flow near the vehicle's rear end. To delay flow separation, bump-shaped vortex generators are tested for application to the roof end of a sedan. Commonly used on aircraft to prevent flow separation, vortex generators themselves create drag, but they also reduce drag by preventing flow separation at downstream. The overall effect of vortex generators can be calculated by totaling the positive and negative effects. Since this effect depends on the shape and size of vortex generators, those on the vehicle roof are optimized. This paper presents the optimization result, the effect of vortex generators in the flow field and the mechanism by which these effects take place.

Key words: *Body, Aerodynamics, Aerodynamic Devices, Flow Visualization, Computational Fluid Dynamics (CFD)*

1. Introduction

To save energy and to protect the global environment, fuel consumption reduction is primary concern of automotive development. In vehicle body development, reduction of drag is essential for improving fuel consumption and driving performance, and if an aerodynamically refined body is also aesthetically attractive, it will contribute much to increase the vehicle's appeal to potential customers.

However, as the passenger car must have enough capacity to accommodate passengers and baggage in addition to minimum necessary space for its engine and other components, it is extremely difficult to realize an aerodynamically ideal body shape. The car is, therefore, obliged to have a body shape that is rather aerodynamically bluff, not an ideal streamline shape as seen on fish and birds. Such a body shape is inevitably accompanied by flow separation at the rear end. The passenger car body's aerodynamic bluffness, when expressed by the drag coefficient (C_D), is generally between 0.2 and 0.5, while that of more bluff cubic objects is greater than 1.0 and that of the least bluff bullets is less than 0.1. Two elements that have major influence on the drag coefficient of a bluff object are the roundness of its front corners and the degree of taper at its rear end. The importance of the influence of the rear taper in passenger cars can be described as follows:

Fig. 1 schematically shows the flow around a sedan. Because of the presence of a trunk at the rear, the flow separates at the roof end and then spreads downward. As a result, the flow around the car is similar to that around a streamline-shaped object with a taper at the rear. For this reason, a sedan with a trunk tends to have smaller drag coefficient value than a wagon-type car.

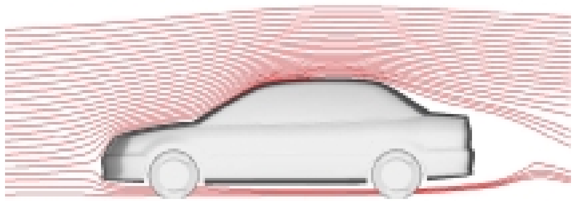

Fig. 1 Flow around a sedan

In other words, taper at the rear has the effect of delaying flow separation (or shifting the flow separation point downstream).

A well-known example for intensifying the flow separation delaying effect is utilizing a dimple (like the ones on golf balls)(1). Adding dimple-shaped pieces can lower the C_D to a fraction of its original value. This is because dimples cause a change in the critical Reynolds number (the Reynolds number at which a transition from laminar to turbulent flow begins in the boundary layer). There are reported examples of aircraft wings controlling the boundary layer, in which vortex generators (hereinafter referred to as VG(s)) successfully delayed flow separation even when the critical Reynolds number is exceeded(2).

Although the purpose of using VGs is to control flow separation at the roof end of a sedan, it is so similar to the purpose of using VGs on aircraft. To determine the shape of sedan VGs, the data on aircraft VGs are referred to(2).

2. Mechanism of flow separation and objectives of adding vortex generators

Fig. 2 shows a schematic of flow velocity profile on the vehicle's centerline plane near the roof end. Since

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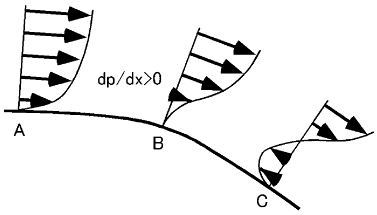

Fig. 2 Schematics of velocity profile around rear end

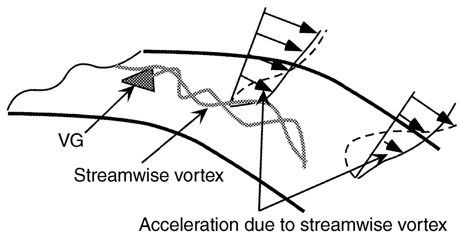

Fig. 3 Schematics of flow around vortex generator

the vehicle height in this section becomes progressively lower as the flow moves downstream, an expanded airflow is formed there. This causes the downstream pressure to rise, which in turn creates reverse force acting against the main flow and generates reverse flow at downstream Point C. No reverse flow occurs at Point A located further upstream of Point C because the momentum of the boundary layer is prevailing over the pressure gradient (dp/dx). Between Points A and C, there is separation Point B, where the pressure gradient and the momentum of the boundary layer are balanced. As shown in **Fig. 2**, in the lower zone close to the vehicle's surface within the boundary layer, the airflow quickly loses momentum as it moves downstream due to the viscousity of air. The purpose of adding VGs is to supply the momentum from higher region where has large momentum to lower region where has small momentum by streamwise vortices generated from VGs located just before the separation point, as shown in **Fig. 3**. This allows the separation point to shift further downstream. Shifting the separation point downstream enables the expanded airflow to persist proportionately longer, the flow velocity at the separation point to become slower, and consequently the static pressure to become higher. The static pressure at the separation point governs over all pressures in the entire flow separation region. It works to reduce drag by increasing the back pressure. Shifting the separation point downstream, therefore, provides dual advantages in drag reduction: one is to narrow the separation region in which low pressure constitutes the cause of drag; another is to raise the pressure of the flow separation region. A combination of these two effects reduces the drag acting on the vehicle.

However, the VGs that are installed for generating streamwise vortices bring drag by itself. The actual effectiveness of installing VGs is therefore deduced by subtracting the amount of drag by itself from the amount of drag reduction that is yielded by shifting the separation point downstream. Larger-sized VGs increase both the effect of delaying the flow separation and the drag by itself. The effect of delaying the flow separation point, however, saturates at a certain level, which suggests that there must be an optimum size for VGs.

3. Experimental methods

Evaluation of the effectiveness of VGs and optimization were conducted using MMC's full scale wind tunnel[3]. The test section was closed and the main flow velocity was set at 50 m/s. Mitsubishi LANCER EVOLUTION VIII was used as the test vehicle. To evaluate the effectiveness of VGs, six component forces of the vehicle were measured and VGs' optimum shape and size were examined. Furthermore, in order to clarify the factors contributing to the effect provided by VGs, the total pressure distribution of the wake flow was measured with pitot rake, the velocity distribution was measured by the particle image velocimetry (PIV) method, and the flow field was analyzed in detail using computational fluid dynamics (CFD).

4. Finding the optimum VGs

To select appropriate shape and size of the VG which generates streamwise vortex the most efficiently (with the least drag by itself) is important to achieve objectives.

In connection with the size, the thickness of the boundary layer is measured based on the assumption that the optimum height of the VG would be nearly equal to the boundary layer thickness. **Fig. 4** shows the velocity profile on the sedan's roof. From this figure, the boundary layer thickness at the roof end immediately in front of the separation point is about 30 mm. Consequently, the optimum height for the VG is estimated to be up to approximately 30 mm.

As to the shape, a bump-shaped piece with a rear slope angle of 25 to 30° is selected. This is based on the fact that a strong streamwise vortex is generated on a hatchback-type car with such rear window angle[4]. A half-span delta wing shape is also recommended for the VG. This shape is inferred from an aircraft's delta wing that generates a strong streamwise vortex at its leading edge[2].

As to the location of VGs, a point immediately upstream of the flow separation point was assumed to be optimum, and a point 100 mm in front of the roof end was selected as shown in **Fig. 5**. The effects of bump-shaped VGs mounted at this point are presented in **Fig. 6**. The front half contour of the bump-shaped VG was smoothly curved to minimize drag and its rear half was cut in a straight line to an angle of approximately 27° for maximum generation of a streamwise vortex. As shown in **Fig. 6**, three bump-shaped VGs that were similar in shape but different in height (15 mm, 20 mm, and 25 mm) are examined. The graph in **Fig. 6** shows that the drag coefficient was smallest at the height of 20 to 25 mm, so a height in this range was considered optimum for the VG. However, a taller VG might cause a

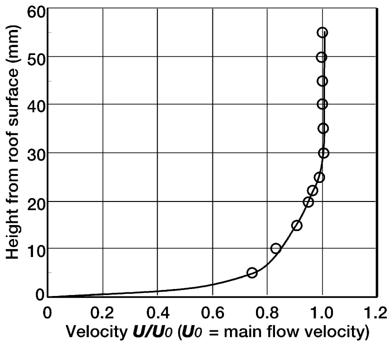

Fig. 4 Velocity profile on roof (100 mm upstream from rear end)

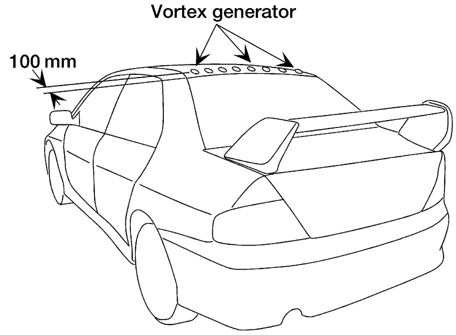

Fig. 5 Location of vortex generators

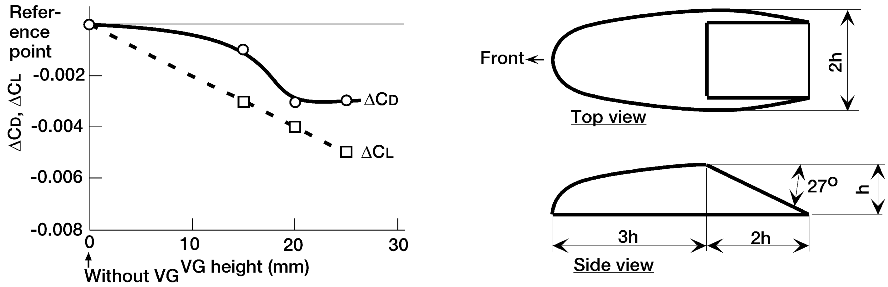

Fig. 6 Effects of bump-shaped vortex generators

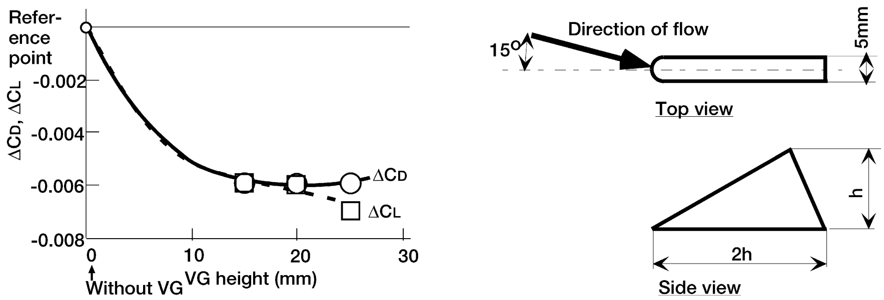

Fig. 7 Effects of delta-wing-shaped vortex generators

decrease in the lift. The rather small change in drag coefficient resulting from change in height can be accounted for as follows. As mentioned before, an increase in height of the VG simultaneously causes two effects: one is reduced drag resulting from delayed flow separation and the other is increased drag by the VG itself. These two effects are balanced when the VG's height is between 20 and 25 mm.

From these results, a reduction of C_D is 0.003 with this bump-shaped VG when the shape and size are optimized.

The effectiveness of the delta-wing-shaped VG is also examined. The recommended shape of the delta-wing-shaped VG is defined by the following[(2)]:

Length/height = 2
Yaw angle = 15°
Interval/height = 6

Based on this data, delta-wing-shaped VGs are created with the following specifications:

Length/height = 2
Height = 15 mm, 20 mm and 25 mm (three types)
Thickness = 5 mm

The delta-wing-shaped VGs should be installed at a yaw angle of 15° to the airflow direction. In order to meet this condition, the direction of airflow at the roof end was investigated by oil flow measurement. Airflow direction was found to be different between sideways positions on the roof. The airflow is aligned directly with the backward direction at center of a car, but it increasingly deviates toward the center as the measurement point shifts away from the central position. For this reason, the delta-wing-shaped VGs must be installed at an angle of 15° against the vehicle centerline for the central position, whereas they must be installed at an angle near 0° for outermost positions. The results of these tests are shown in **Fig. 7**. Delta-wing-shaped VGs were found to be less sensitive to change in height than bump-shaped VGs; the drag reduction effects for the VGs of three different heights

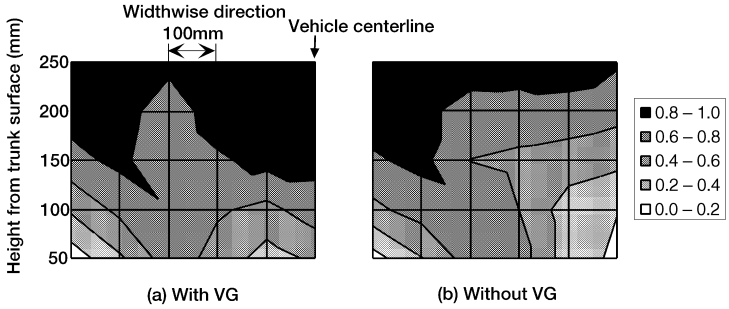

Fig. 8 Total pressure distribution (upstream of rear spoiler)

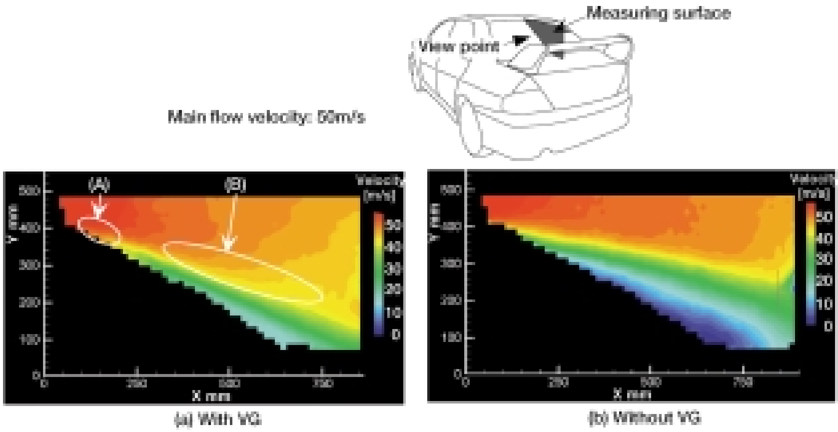

Fig. 9 Velocity distribution by PIV measurement

(15 mm, 20 mm and 25 mm) were all equivalent to –0.006. The effect of lift reduction increased only slightly with the height. The drag reduction also differed only slightly with changes in the number of VGs and their positions. The number and positions of the tested VGs seems to be in their optimum ranges.

From these results, delta-wing-shaped VGs were capable of reducing drag by –0.006.

The reason for why delta-wing-shaped VGs are more effective than bump-shaped VGs can be explained as follows: Delta-wing-shaped VGs have a smaller frontal projection area, which means that they themselves create smaller drag. Moreover, the vortex generated at the edge of a delta-wing-shaped VG keeps its strength in the flow downstream of the edge since it barely interferes with the VG itself because of the VG's platy form. With bump-shaped VGs, on the other hand, the vortex is generated at a point close to the downstream edge of the bump, which causes the vortex to interfere with the bump and lose its strength.

5. Verification of VG's mechanism

In Section 2 above, the effect of VGs is estimated that the separation point is shifted to downstream, which in turn narrows the flow separation region. The flow field was thus investigated in order to verify the correctness of this estimation.

Fig. 8 shows total pressure distribution in the wake flow immediately upstream of the rear spoiler for both cases with and without VGs. High total pressure regions correspond to high velocity regions. As the figure shows, the high velocity region is expanded downward by addition of VGs, signifying that the flow separation region is narrowed.

Fig. 9 shows the results of velocity distribution using the PIV method. The PIV laser light sheet was illuminated from above on the center plane of the vehicle body and the measuring surface was photographed from the side (as indicated by the viewpoint arrow in **Fig. 9**) to calculate the two-dimensional velocity distribution. **Fig. 9 (a)** shows the velocity distribution for the case with VGs, and **Fig. 9 (b)** shows the velocity distribution for the case without VGs. As evident from the figure, the case with VGs shows an increase in velocity on the surface of the body (rear window) just behind the VG (Zone A in the figure) and extension of the high velocity zone downward (Zone B in the figure). This supports our estimation in the previous section that VGs cause airflows above the rear window to attach to the surfaces of the body.

This phenomenon was examined in detail using CFD analysis. Star-CD was used as the solver and RNG k-ε model as the turbulence model in this analysis. In order to detect flow separation at the rear window, a prism cell was inserted in the vicinity of the vehicle, and the "y+" value of computational grid is arranged to become an appropriate value between 20 and 50 near the separation point. **Fig. 10** shows the calculation results for the case with VGs and the case without VGs. These results show good agreement with the experimental results using the PIV method, and clearly show that the

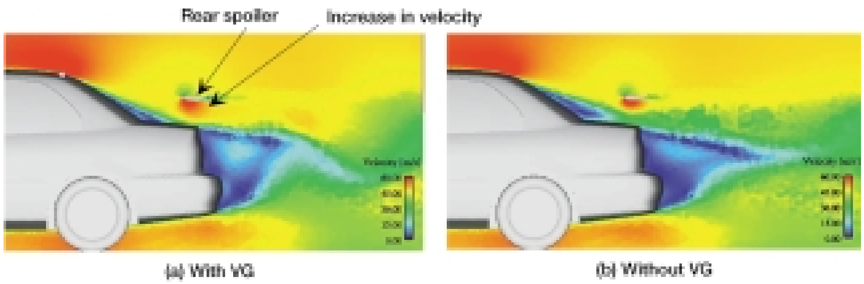

Fig. 10 Velocity distribution by CFD

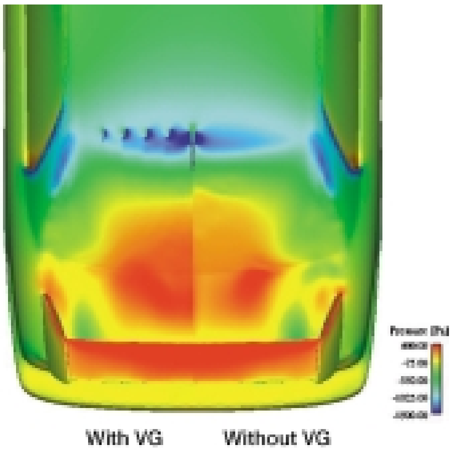

Fig. 11 Pressure distribution of vehicle (CFD)

low velocity region is narrowed by the addition of VGs. The changes in drag and lift calculated by CFD shown below are almost agree with the experimental results (**Fig. 7**).

$\Delta C_D = -0.004$
$\Delta C_L = -0.013$

The CFD calculation, therefore, could simulate the actual phenomenon. CFD results in **Fig. 10** also show that the velocity of the airflow along the bottom surface of the rear spoiler increases by addition of VGs, which reveals that a decrease in lift (an increase in down-force) did occur. These results also show that the flow separation region (low velocity region) at the rear portion of the trunk is slightly narrowed.

Fig. 11 shows the pressure distribution on the vehicle body surface. The addition of VGs gives the effect of increasing the surface pressure over a wide area ranging from the rear window to the trunk and this in turn reduces the drag. However, negative pressure region around the VGs indicate that VGs themselves cause drag.

Such changes in airflow can be attributed to VGs that work to suppress flow separation at the rear window. To verify this mechanism, the airflow was studied in further detail. **Fig. 12** shows vorticity distribution behind the VGs. Streamwise vortices are generated behind the VGs.

Our estimation that the streamwise vortex causes the separation point to shift downstream is confirmed by CFD results. **Fig. 13** shows close-up views of the flow field near the separation point. The case with VGs shows flow separation occuring further downstream than in the case without VGs.

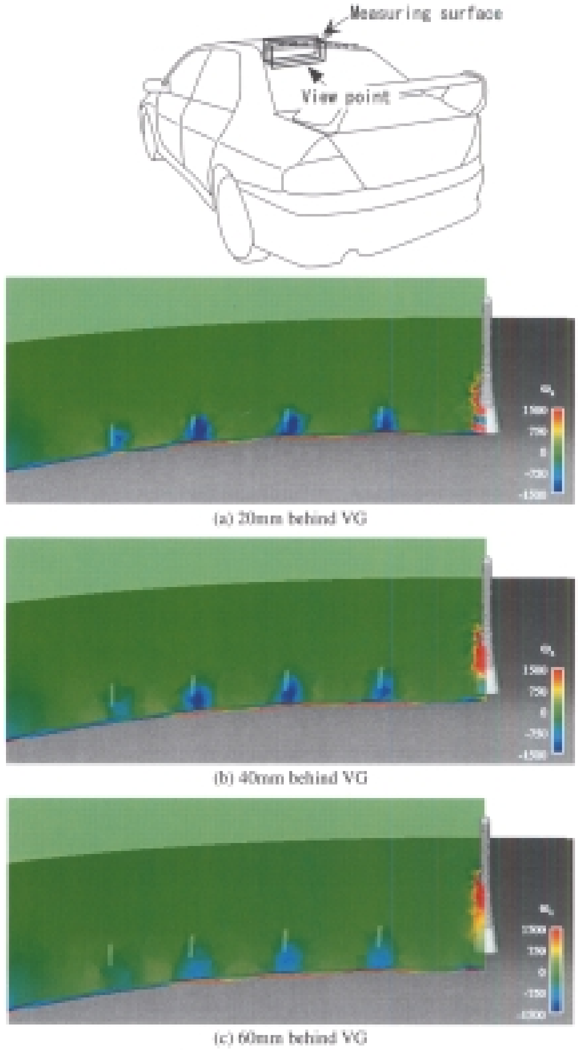

Fig. 12 Vorticity distribution behind vortex generators (CFD)

6. Conclusions

The conclusions of this research can be summarized into the following points:

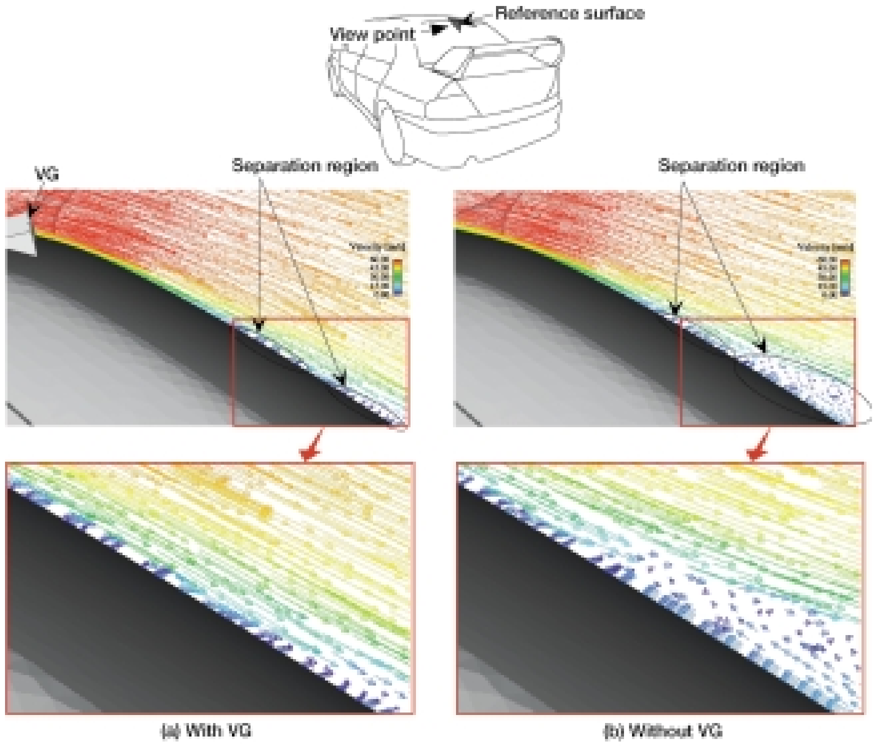

Fig. 13 Velocity vectors around separation point (CFD)

(1) Vortex generators (VGs) were studied to install immediately upstream of the flow separation point in order to control separation of airflow above the sedan's rear window and improve the aerodynamic characteristics. It was found that the optimum height of the VGs is almost equivalent to the thickness of the boundary layer (15 to 25 mm) and the optimum method of placement is to arrange them in a row in the lateral direction 100 mm upstream of the roof end at intervals of 100 mm. The VGs are not highly sensitive to these parameters and their optimum value ranges are wide. Better effects are obtained from delta-wing-shaped VGs than from bump-shaped VGs.

(2) Application of the VGs of the optimum shape determined through the abovementioned analyses to the Mitsubishi LANCER EVOLUTION showed a 0.006 reduction in both the drag coefficient and lift coefficient.

(3) Factors contributing to the effect of VGs were verified by conducting measurement of total pressure, velocity distribution and CFD. As a result of the verifications, it is confirmed that VGs create streamwise vortices, the vortices mix higher and lower layers of boundary layer and the mixture causes the flow separation point to shift downstream, consequently separation region is narrowed. From this, we could predict that VGs cause the pressure of the vehicle's entire rear surface to increase therefore decreasing drag, also the velocity around the rear spoiler to increase, and the lift to decrease.

The delta-wing-shaped VG, which demonstrated high effectiveness in this research, is planned for commercialization as an accessory for sedans after slight modifications to the shape with respect to design, legal conformance and practicality.

References

(1) Hoerner, S. F., Fluid-dynamic Drag, Published by the author, 1958

(2) Hoerner, S. F., Fluid-dynamic Lift, Published by the author, 1985

(3) Shibata, H., MMC's Vehicle Wind Tunnel, Automobile Research Review (JARI) Vol. 5, No. 9, 1983

(4) Hucho, W. H., Aerodynamics of Road Vehicles, Fourth Edition, SAE International 1998


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