Passive Control of Turbulent Flow behind a Model Vehicle for Drag Reduction Using Wake Disrupter

Dongkon Lee[*], Jin Choi[*], Woo-Pyung Jeon[**], Jeonglae Kim[*],
Seonghyeon Hahn[**] and Haecheon Choi [*, **]
[*] *School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, Korea*
[**] *Center for Turbulence and Flow Control Research, Institute of Advanced Machinery and Design, Seoul National University, Seoul 151-744, Korea*

Summary Both wind-tunnel experiment and large eddy simulation are carried out to examine the applicability of a new passive device, wake disrupter, to flow over a model vehicle for drag reduction. The wake disrupter is a small-size rectangular body attached to a part of the trailing edge of the model vehicle, designed to perturb an essentially two-dimensional nature of wake. The wake disrupter significantly changes the wake structures and leads to maximum 23% increase in the base pressure of the model vehicle.

The development of a highly efficient transportation vehicle is one of the most important issues for control of turbulent flow for drag reduction. Generally, for large-scale transportation vehicles, the separation point is fixed at the trailing edge where the flow suddenly changes from a flat-plate boundary layer flow to a wake. Some experiments on control of flow over a model vehicle with a fixed separation point have been conducted for drag reduction using splitter plate and base bleed [1-2]. For a successful drag reduction, however, relatively large-size plate and high blowing rate were required in those studies. The spanwise modifications of the tailing edge such as segmented, curved, M-shaped and sinusoidal edges have also led to significant drag reductions [3,4], but the amounts of shape modification were quite large. Therefore, an effort toward designing a small-size passive device is needed for practical implementation. Very recently, Kim & Choi [5], and Kim et al. [6] suggested an active control method (called distributed forcing) for drag reduction on a circular cylinder and on a two-dimensional model vehicle, respectively, where the forcing (blowing and suction) varied sinusoidally in the spanwise direction but was steady in time. They showed that vortex shedding with the distributed forcing is attenuated for both laminar and turbulent flows and thus drag is significantly reduced. In the present study, a wake disrupter, inspired from the distributed forcing, is proposed as a new passive device to control the turbulent flow behind the model vehicle for drag reduction and its effect is examined by both the wind-tunnel experiment and large eddy simulation (LES).

In our experiment, the model vehicle is made of ABS copolymer and its nose is shaped into a half ellipse with its ratio of the major to minor axis of 8, following Tombazis and Bearman [4] (see Figure 1). A trip wire, which is a chain of spheres with the diameter of 2mm, is attached to both the upper and lower body surfaces at the 100mm downstream location from the nose of the model vehicle. Three different free-stream velocities of 5, 10 and 20 m/s are considered and the corresponding Reynolds numbers are Re_h =20000, 40000 and 80000, respectively. The wake disrupter is a small-size rectangular body attached to a part of the trailing edge of the model vehicle (Figure 1). A pair of wake disrupters is mounted on the mid-span at the upper and lower trailing edges. The l_y and l_z are the sizes of wake disrupter in the wall-normal and spanwise directions, respectively. The 71 cases with the different l_y's and l_z's are tested to determine the optimum-size disrupter for maximum drag reduction. For all the cases, the base pressures are measured on the flat base surface. The momentum and boundary layer thicknesses measured by a hot-wire probe are 1.02mm (Re_q =680) and 13.3mm, respectively, at x/h= -0.033 for Re_h =40000.

Large eddy simulation with a dynamic subgrid-scale model is also carried out for flow over a model vehicle at Re_h =4200. In LES, only the flow field over the rear part of the model vehicle is simulated in a Cartesian coordinate system with a turbulent boundary layer flow of Re_q =670 introduced at the domain inlet. The ratio of the boundary layer thickness at the domain inlet to the body height (d/h = 1.4) is much larger than that in our experiment (d/h = 0.22). An immersed boundary method [7] is used to simulate the flow with the wake disrupter.

The contour plot in Figure 2 shows the percentages of spanwise-averaged base-pressure variation with respect to l_y and l_z at Re_h =40000. Here, l_y and l_z are scaled by the length scales (d and q) of the boundary layer just upstream of the fixed separation point (x/h= -0.033) as well as the height of the model (h). The symbol in this figure corresponds to the actual experimental measurement. For most of disrupters, the base pressure is increased, indicating drag on the model vehicle is decreased except that for $0 < l_y/h < 0.66$ and $0 < l_z/h < 0.033$, where the base pressure is slightly decreased. The maximum increase in the base pressure is about 23% with the optimal wake disrupter having the sizes around $l_y/h = l_z/h = 0.23$. Similar results are obtained at Re_h =20000 and 80000.

As for the LES result, Figure 3 shows the iso-surfaces (top view) of pressure behind the model vehicle for the cases without and with wake disrupter (l_y/h =0.2, l_z/h = 0.2). For the uncontrolled flow, the large-scale two-dimensional Karman vortex cores can be clearly found. However, with wake disrupter, the Karman vortex cores are broken up into some smaller-scale vortices and the wake becomes completely three-dimensional.

In conclusion, the wake disrupter is very effective in reducing drag on a two-dimensional model vehicle at various Reynolds numbers where the separation point is fixed.

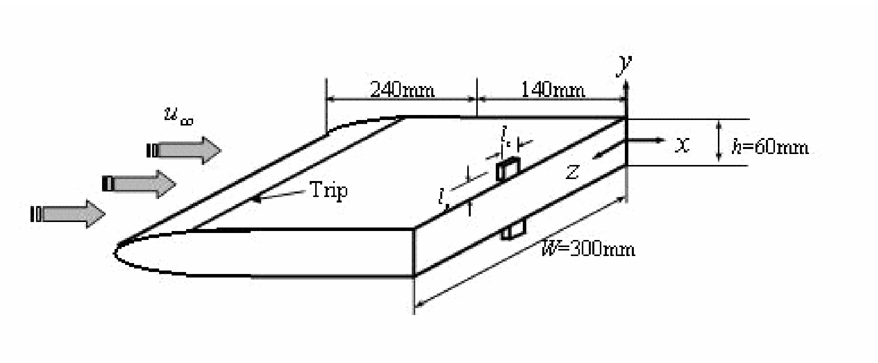


Figure 1 Schematic of the model vehicle and wake disrupter.

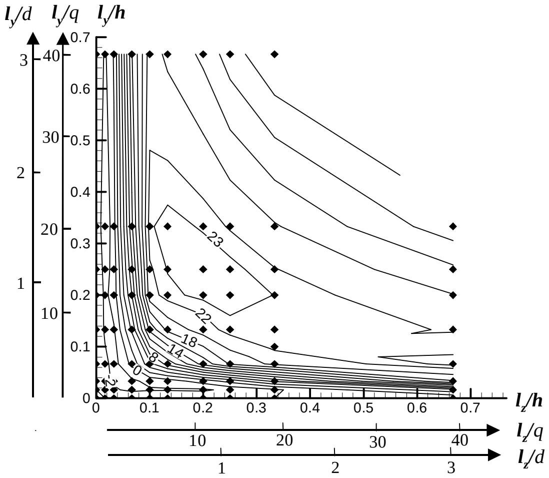
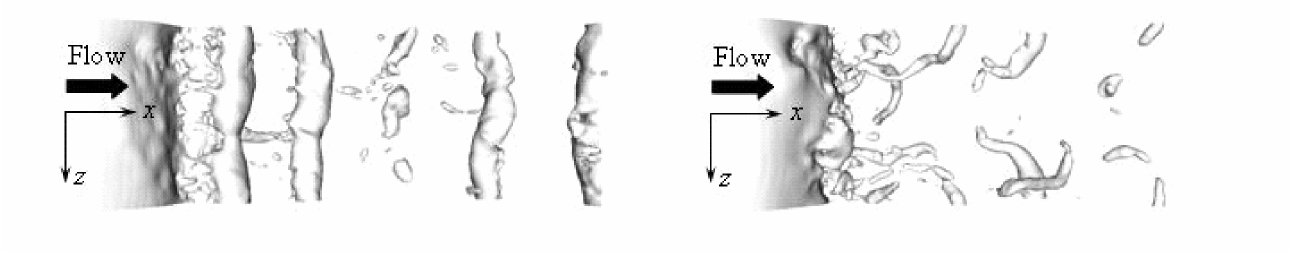


Figure 2 Contours of the spanwise-averaged base-pressure variation (%) with respect to l_y and l_z at Re_h =40000.



Without disrupter

With disrupter (l_y/h =0.2, l_z/h = 0.2)

Figure 3 Iso-surfaces of the pressure behind the model vehicle at Re_h =4200.

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