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Substantial drag reduction of a tractor-trailer vehicle using gap fairings

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ABSTRACT

Aerodynamic drag reduction of heavy vehicles is one of the main issues in fuel saving and environmental gas emission. In general, 50% of the total aerodynamic drag is induced from the region in the front surface of the vehicle and the gap between the tractor and trailer. Various forebody drag-reducing devices for tractor–trailer vehicles were introduced, however, conventional gap fairings or side extenders have technical limitations in reducing the aerodynamic drag exerting on the cab-roof space and gap between the tractor and trailer effectively. In this study, wind tunnel tests were conducted to investigate the drag reduction effects of the newly proposed gap fairings. The proposed gap fairing reduced drag by 16.4% at maximum as well as changed the gap length and deflecting angle. The aero cab fairing (ACF), which is a combination of cab-roof and gap fairings, and the extended aero cab fairing (EACF) considerably reduced the drag coefficient by approximately 11.1% and 17.5%, respectively. A particle image velocimetry was used to investigate flow characteristics, such as spatial distributions of mean velocity, vorticity, and turbulent kinetic energy around the scaled-down tractor–trailer model (1:17) with and without gap fairings to analyze the drag-reduction mechanism of the proposed gap fairings. The proposed gap fairings including ACF and EACF significantly reduced the mean velocity, vorticity in the gap region between the tractor and trailer, and the turbulent kinetic energy on the trailer's front surface. Results can provide useful information for improving the design of new additive flow control devices in reducing the aerodynamic drag of heavy vehicles.

1. Introduction

Improvement of aerodynamic characteristics of road vehicles could contribute to the solutions for fuel-saving and air pollution issues. In particular, 16% of the total energy consumed in the United States was used to overcome aerodynamic drag of transportation systems (Wood, 2003). Many studies have been conducted to determine effective strategies in reducing aerodynamic drag of heavy vehicles. These aerodynamic strategies have largely improved the fuel efficiency of heavy vehicles (Hucho and Sovran, 1993).

Various kinds of drag-reducing devices have been introduced to effectively reduce the aerodynamic drag of heavy vehicles, including cab-roof fairing (CRF), gap fairing, side extenders, side skirts, and boat tail (Cooper, 2003; Hwang et al., 2016; Khalighi et al., 2001; Waltzer et al., 2015). Detailed information for these drag-reducing devices and their drag-reduction effects have been summarized in a review paper (Choi et al., 2014).

The flow passing through the gap between the tractor and trailer of heavy vehicles has to be controlled effectively because approximately 20% of the aerodynamic drag is induced by the gap of heavy vehicles running on a highway (Wood, 2006). Hammache and Browand (2004) reported a significant increase in the drag coefficient of trailers when the gap width is larger than a critical value.

Several strategies for reducing drag induced by gap flow were suggested, such as gap enclosure (Allan, 1981), cab side extender (Castellucci and Salari, 2005; Hyams et al., 2011; Storms et al., 2004), and tractor base bleeding (Ortega and Salari, 2004). Among these strategies, gap fairing is similar to the concept of “side extender” and has been widely used as a drag-reducing device to handle the gap flow. Gap fairing was reported to reduce the forebody drag of heavy vehicles by approximately 7% at a driving speed of 55 mph (Cooper and Leuschen, 2005). Gap fairing delays flow separation on the tractor, pushing the low-pressure region away from the tractor base, thereby decreasing the drag force exerted on the trailer (McCallen et al., 2005).

However, reduction of aerodynamic drag induced by the gap of between the tractor and trailer because of a large flow separation on the side surfaces of the gap fairing is limited. Kim et al. (2017a,b) proposed a CRF that can modify flow on the side surfaces, which further improved drag reduction effect compared with commercial CRF devices. Therefore, modifying the external geometric configuration of the gap fairing

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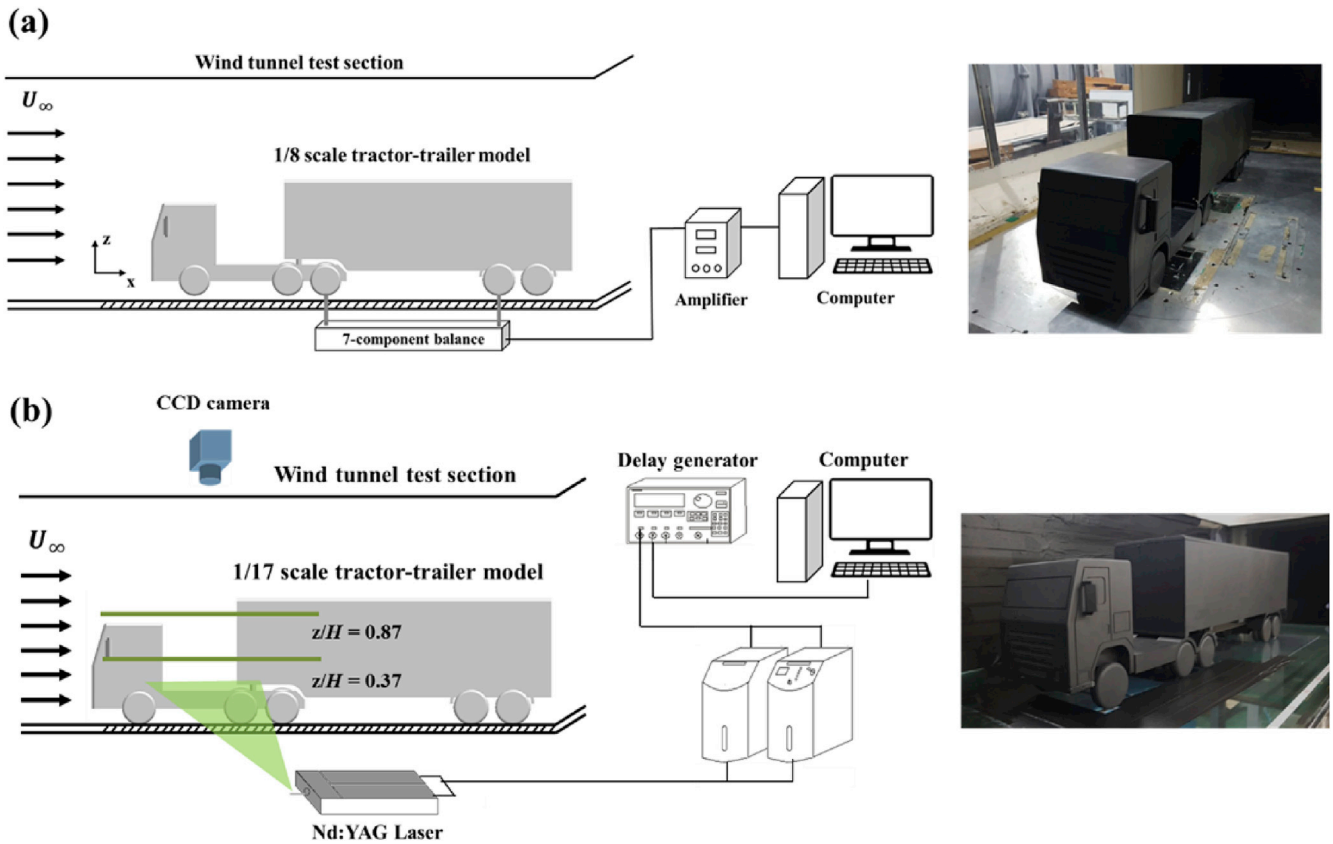

Fig. 1. (a) Schematic diagram (left) and photograph of the vehicle model (right) installed in the wind tunnel test section with drag measurement system. (b) Schematic diagram (left) and photograph of the vehicle model (right) used for PIV velocity field measurements. The PIV system consists of a 120 mJ Nd:YAG laser, a 4 K × 3 K CCD camera, a delay generator, and a PC.

especially for the side surfaces, can delay the flow separation and block the inward flow on the side surfaces of the gap fairing more effectively, thereby reducing aerodynamic drag of tractor–trailer vehicles.

In the present study, the proposed gap fairings installed at the gap between the tractor and trailer of heavy vehicles are designed to reduce effectively the aerodynamic drag. The proposed gap fairings were fabricated using a 3D printer. Its drag-reduction effects were evaluated quantitatively for a scaled-down (1:8) wind tunnel model of a 40 ft tractor–trailer heavy vehicle. A particle image velocimetry (PIV) velocity field measurement technique was used to measure flow characteristics (e.g., spatial distributions of mean velocity, mean vorticity, and turbulent kinetic energy) around the scaled-down vehicle model (1:17) with and without gap fairings to determine the drag-reduction mechanism.

2. Experimental apparatus and method

2.1. Drag measurement of vehicle models

POSTECH subsonic wind tunnel with a test section of 1.5 m (height) × 1.8 m (width) × 4.3 m (length) was used to conduct wind tunnel tests on a vehicle model (Fig. 1a). The free stream velocity was changed from $U_\infty = 7$–30 m/s, and the corresponding Reynolds number was $2.6 \times 10^5 \leq Re \leq 1.1 \times 10^6$. The turbulence intensity of the free stream flow was less than 0.2%.

The aerodynamic drag exerted on the vehicle model was measured using a seven-component external balance (German Aerospace Center Stuttgart (DLR)). The measurement accuracy of the drag force was within the error level of 0.2%. The forces along the streamwise (x-axis) and spanwise (y-axis) directions were estimated by statistically averaging the data obtained from at least five replication experiments. The vehicle model was placed on the external balance by connecting its front and rear wheels to four contacts of the balance.

The crosswind effect on the aerodynamic forces exerted on the vehicle model was measured by rotating the turntable that supports the vehicle model and the balance to vary the yaw angle in the range of 0°–15°. The drag force (F_D) of the vehicle model and the corresponding drag coefficient (C_D) were obtained using following equations:

$$F_D = F_x \cos\left(\frac{\pi}{180}\phi\right) + F_y \sin\left(\frac{\pi}{180}\phi\right), \quad C_D = \frac{F_D}{\rho A U^2/2},$$

where F_x and F_y denote the drag force measured along the streamwise and spanwise directions, respectively, ρ is the air density, U is the wind speed, ϕ is the yaw angle, and A is the frontal cross-sectional area of the vehicle model.

2.2. PIV measurement

Fig. 1b illustrates a schematic diagram of the PIV system used to measure the velocity fields of the flow around the vehicle model. PIV experiments for a scaled-down (1:17) vehicle model were conducted at another closed-return subsonic wind tunnel with a test section of 0.72 m (width) × 0.6 m (height) × 6.75 m (length). Free stream velocity was fixed at $U_\infty = 15$ m/s, which corresponded to Re = ~3×10^5. The turbulence intensity of the free stream flow in the test section was less than 0.08% at $U_\infty = 15$ m/s; hence, the flow structure around the vehicle model can be measured accurately (Gerrard, 1966). The PIV system consists of a two-headed Nd:YAG pulse laser of 120 mJ, a CCD camera (4 K × 3 K), a delay generator, optical lenses used to form a thin laser light sheet, and a PC for image acquisition and data analysis. Olive oil droplets with a mean diameter of 1–3 μm were used as tracer particles in PIV experiments. Oil droplets generated from the Laskin nozzle were seeded into the wind tunnel test section. Spatial distributions of mean velocity, vorticity, and turbulent structural information were obtained by

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