Optimum nose shape of a front-rear symmetric train for the reduction of the total aerodynamic drag

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Abstract

For a high-speed train, the same power car is used as the first car and as the last car in a reverse direction simultaneously. Therefore, the previously optimized nose shape, considering only the first car position, is not well adopted in the last car position of a front-rear symmetric train in view of the aerodynamic drag. The three-dimensional nose shape optimization of a front-rear symmetric train is conducted to minimize the total aerodynamic drag of the entire train using CFD. The 3-D nose model is constructed by the vehicle modeling function with the optimized area distribution to minimize the micro-pressure wave. It is revealed that the total aerodynamic drag of the optimum shape for the entire train is reduced by 23.0% when compared to that of the conventionally optimized shape only for the first car of the symmetric train.

Keywords: 3-D nose shape; Aerodynamic drag; Design optimization; Front-rear symmetric train; Vehicle modeling function; Wake area simulation

1. Introduction

Innovative models of ultra-high-speed trains that are capable of speeds exceeding 300 km/h are now being developed in many parts of the world [1]. Because aerodynamic problems appear more seriously as trains run even faster, much active research about aerodynamic phenomena is being performed [2-4]. Various studies are being conducted for the primitive geometry, a real train, numerical or experimental techniques, and the ground effect [5-7].

One of the most serious aerodynamic problems is the aerodynamic drag of the total running resistances in the open field. The aerodynamic drag takes much greater parts of the running resistance as the train speed increases, and it also increases proportionally to the square of the train speed. Another issue is micro-pressure waves at the tunnel exit, especially considering that the portion of the tunnel to the total line is extremely high in mountainous countries such as Korea and Japan. A micro-pressure wave is created at the tunnel exit due to a train’s piston movement against the air inside the tunnel, as shown in Fig. 1 [8, 9]. It is well known that the aerodynamic characteristics of a high-speed train are strongly influenced by the external shape of the train [10, 11]. Most of all, the train’s nose has the greatest effect on the aerodynamic phenomena of a high-speed train [10]. The aerodynamic drag is mainly affected by the three-dimensional shape of the noses of the first car and the last car. On the other hand, the micro-pressure wave is primarily influenced by the cross-sectional area distribution of the nose of the first car. Various nose shape optimizations have been performed in consideration of external nose shapes. Lorriaux et al. optimized the two-dimensional nose shape with numerical solver and the genetic algorithm [12]. Krankovic proposed the optimization procedure for the cross-wind stability of the nose of the first car and one for the aerodynamic drag reduction with vortex generators at the last car [13]. Vytal et al. optimized the two-dimensional nose shape to minimize both the aerodynamic drag and the aerodynamic noise [14]. Kwon et al. optimized the axi-symmetric...
nose shape to reduce both the aerodynamic drag and the micro-pressure wave [15]. Ku et al. carried out the two-stage design optimization of the nose shape for the micro-pressure wave and the aerodynamic drag [16, 17]. They obtained first the optimized one-dimensional cross-sectional area distribution of the nose of the first car for the reduction of the micro-pressure wave, and then optimized the three-dimensional nose shape of the first car to reduce the aerodynamic drag maintaining the cross-sectional area distribution obtained during the first stage.

The total aerodynamic drag is mostly influenced by the first car nose and the last car nose [4]. However, the wake area behind the last car was not simulated appropriately in the previous studies. The wake area behind the two-dimensional shape is different from that behind the three-dimensional body. The ground cannot be simulated for the axi-symmetric body and the different wake area is induced by no ground simulation. Thus, the entire train including the first car nose and the last car nose has to be considered at the same time for the three-dimensional nose shape optimization of a front-rear symmetric train with the goal of reducing the total aerodynamic drag.

The aim of the present study is to obtain a three-dimensional optimum aerodynamic nose shape of a front-rear symmetric train to reduce the total aerodynamic drag under the constraint of the minimum micro-pressure wave. Using this solution, three-dimensional train models are constructed with the constraint of the cross-sectional area distribution optimized for the reduction of the micro-pressure wave in the previous research [1]. Because all the train models satisfy the constraint, they automatically show the minimum micro-pressure wave. A viscous compressible flow solver is adopted with unstructured meshes to predict the aerodynamic drag. Noise shape optimizations are performed for the reduction of the total aerodynamic drag of the entire train and of only the aerodynamic drag of the first car respectively. The optimization results for the total aerodynamic drag are compared to those of the optimization for the aerodynamic drag of the first car by the previous method for the reduction of design time.

2. Methodology

The aerodynamic drag of each train model is predicted by a viscous compressible solver at an operating speed of 500 km/h.

2.1 Numerical method

Unstructured grids are employed to form the grids of complex shapes. A three-car streamlined train model without bogie wheel is used as the analysis model, as the trains become shorter and the portion of the pressure drag due to both noses increases as the operating speed of the train increases. The grid geometry during the numerical simulation is based on a three-car front-rear symmetric train composed of the first car, an intermediate car, and the last car, as shown in Fig. 2. The nose of the first car is the first car nose and that of the last car is the last car nose. The length of both noses is 15 m which is the longest length of the optimized cross-sectional area distribution shapes by Ku et al. because longer noses induce less aerodynamic load as the train speed increases [1]. The length of both end cars (the first car and the last car) is 25.9 m while the length of the intermediate car is 24.3 m. The dimensions of the entire train model are 3.09 m (width), 3.52 m (height), and 76.1 m (length). They are determined according to HEMU-430x, a Korean high-speed train under development [18]. The computational domain is shown in Fig. 3. Ten boundary prism layers are applied to simulate the viscous flow in the vicinity of the train model more accurately, as shown in Fig. 4. Their total thickness is about 0.032 m. All of the surfaces of the train model are a stationary wall and no slip condition is applied. To simulate the train’s motion relative to the ground, a moving ground condition is applied to the only ground surface. The gap between the train model’s bottom surfaces and the ground is 0.1 m according to the condition of Ref. [19]. The grid in the computational domain contains about 10 million cells.

In this study, the commercial CFD solver, ANSYS Fluent is used. The governing equations are the three-dimensional compressible Navier-Stokes equations, as shown below [20].