Study on the Aerodynamic Performance of the High-Speed Train Head with Symmetrical and Asymmetric Nose Shape

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ABSTRACT

This study focused on the use of mesh morphing on optimizing high-speed train shape. Three shape variables were studied in this paper: the angle of cab-window, length of train-nose and width of train-nose. The original high-speed train head was optimized in symmetrical and asymmetric deformation. Total drag coefficient and lift coefficient of head car and tail car were optimized using Kriging model and NSGA-II. As a result, three objective aerodynamic performance of the optimal train in symmetrical deformation is slightly improved comparing with the original ones and that in asymmetric deformation is improved significantly. Also, results of the symmetrical and asymmetric optimized high-speed train running in different speed were compared with that of the original high-speed train. Proposed method in this paper has been proved to be an efficient and feasible approach to study and optimize the aerodynamic performance of different high-speed trains as well as other structures.

1. INTRODUCTION

Energy conservation has rapidly increased its importance in high-speed train design with the increase of its running speed. However, aerodynamic drag acting on
a moving high-speed train accounts for 75% of the total resistance\textsuperscript{[1]} when a high-speed train is running in the open air without crosswind at the speed of 300 km/h. The most effective way to decrease energy cost is to reduce the aerodynamic drag force of the high-speed train. Thus, the optimization of high-speed train shape is indispensable in high-speed train design\textsuperscript{[2]}.

With the development of computational fluid dynamics, numerical simulation has become a critical method to investigate the aerodynamic performance of high-speed trains with different head shapes. Besides, surrogate-based optimization has been introduced into aerodynamic optimization of high-speed train shape and significantly improved the efficiency of the optimization. Lorriaux et al.\textsuperscript{[3]} and Vylta et al.\textsuperscript{[4]} carried out geometrical optimization on minimizing aerodynamic drag of high-speed train head based on surrogate models. Kranjnovic\textsuperscript{[5]} compared three types of Response Surface Method (RSM) models in the optimization of geometry variables of high-speed train head, aiming at minimizing the drag coefficient, the rolling moment coefficient and the yawing moment coefficient under crosswind. Munoz-Paniagua et al.\textsuperscript{[6]} optimized a simple three-dimensional high-speed train head, taking drag and the Maximum Micro-Pressure Wave as objectives in the application of a genetic algorithm based on a surrogate model. As the other key step, parameterization of high-speed train head has been concerned by many researchers. Yao et al.\textsuperscript{[7]} performed the optimization on aerodynamic elements of high-speed train by parameterizing B-spline of high-speed train surface.

Mesh morphing has been introduced in the latest researches on aerodynamic optimizations. Li et al.\textsuperscript{[8]} optimized the aerodynamic drag and lift force of a high-speed train head using the Free Form Deformation method in mesh morphing. Some researchers\textsuperscript{[9,10]} demonstrated that Radial Basis Function (RBF) interpolation is a feasible mesh-less approaches to computational fluid dynamics (CFD) mesh morphing. The RBF Morph interpolation has been implemented to perform shape optimization in many industrial fields including sails trim optimization, motorbike windshield optimization, aircraft optimization and so on. Examples can be found in studies by Biancolini et al.\textsuperscript{[11,12]}. Mesh morphing will improve the efficiency of the aerodynamic shape optimization based on CFD simulations as new shapes are generated only by moving mesh node in interested region of the original CFD model without rebuilding and re-meshing process.

The aerodynamic drag and lift forces in the head car, middle car and tail car of the high-speed train are different due to the specific flow structure around the high-speed train in the open air without crosswind\textsuperscript{[13,14]}, asymmetric deformed optimization of the head car and tail car should be considered to improve its aerodynamic performance. However, few studies have been focused on the asymmetric structure of the head shape of high-speed trains. With considering three shape parameters of the high-speed train head, this paper optimized the total drag coefficient and lift coefficient of head car and tail car using mesh morphing and surrogate-based optimization. Symmetrical deformed and asymmetric deformed optimization were carried out and the optimization results were analyzed and
compared to find out a more effective way in the optimization of the aerodynamic optimization of high-speed train.

2. METHODS

2.1 Aerodynamic optimization of high-speed train head

The traditional optimization procedure requires to reconstruct geometric models of different high-speed train head and re-mesh the computational domain. Aerodynamic optimization of the high-speed train head using mesh morphing method deform the original grid instead of rebuilding different geometry models and re-meshing the computational domain, which saves the optimization time and improves the optimization efficiency.

Figure 1 shows the flow chart of the high-speed train head optimization method based on mesh morphing method. This method is basically the same as that of the high-speed train head type optimization method, which is composed of high-speed train shape parameterization modeling and experiment design. The construction of the approximate model and optimization process is as follows:

(1) Determine design parameters of the high-speed train head and aerodynamic optimization objectives, such as aerodynamic drag and lift force, pressure wave, aerodynamic noise and so on.

(2) Establish the computational domain of the initial high-speed train model and mesh. Determine the high-speed train head design parameters and establish the parameterized model of the high-speed train head by control points.

(3) Carry out design of experiment (DOE), determine the sample points in design ranges, deform the original grid the high-speed train model to match different parameters of the sample points and carry out CFD aerodynamic simulation to obtain the target aerodynamic performance of the sample points.

(4) Construct the surrogate model(s) of the design parameters and the target responses according to the experimental design results. If the prediction error meet the requirements, proceed to the next step, otherwise reconstruct the surrogate model(s).

(5) Optimize the determined objectives using the surrogate model(s). The optimization process includes design parameter initialization and iterative solution. If the optimization process converges, end the optimization, proceed to the next step, otherwise re-optimize.

(6) Verify the optimization results using CFD numerical simulations. If the optimized target aerodynamic performance is improved, end the optimization, otherwise return (3) to repeat the DOE, surrogate model(s) construction and optimization.

In this paper, the head-type of the high-speed train was optimized using RBF grid deformation method, which not only improves the efficiency of optimization greatly and avoids the noise introduced by re-meshing but also opens up the barrier between
the parameterization and design of the high-speed train, the surrogate model and the optimization process. This method is a quick and easy way to optimize the head shape of high-speed train.

In this study, 13 samples and 28 samples were generated for symmetrical and asymmetrical optimization of the high-speed train head respectively. The design ranges for cab-window area, nose-length and nose-width are elaborated in Table 1. The limitations were set to prevent distortions in the train surface. Deformation of the specific parameters was elaborated in Fig. 2. The Kriging surrogate models of the design parameters and aerodynamic responses including the drag and lift coefficient were constructed to describe the relationships between them. The aim of the optimization is to achieve a group of minimized total drag coefficient and lift coefficient of head car and tail car.

Figure 1. Optimization of high-speed train head based on mesh morphing.
2.2 CFD simulation

The flow around a high-speed train in the open air with no crosswind is considered to be three-dimensional incompressible steady viscous flow. Therefore, Reynolds-Averaged Navier-Stokes equations based on the finite volume method were used to predict the aerodynamic characteristics of the flow around a high-speed train in a CFD simulation. The SIMPLEC (Semi-Implicit Method for Pressure Linked Equations-Consistent) algorithm was selected as the velocity correction method, and the QUICK (Quadratic Upstream Interpolation for Convective Kinematics) scheme was used to solve the steady convection–diffusion equation because it is third-order accurate in space and first-order accurate in time.

The 3 car formatted high-speed train in 1:1 scale running in the open air without crosswind at the speed of 300 km/h was simulated in this study. The computational domain was modeled to simulate the flow around the high-speed train. The domain size was determined according to the characteristic length $L$, which equals to the train length, as shown in Fig. 3. The distance between the wheel and the ground is 0.2 m, representing the height of rail tracks. Fig. 4 shows the grids on the nose, the bogie and the gap.
3. RESULTS AND DISCUSSION

After the optimization, 628 and 408 Pareto solutions were obtained for symmetrical and asymmetrical optimization respectively in 2500 iterations. Although the Pareto-set can provide designer with a large number of design solutions, decision must be made for the most satisfactory solution (termed as “knee point”) from Pareto-set finally. In this paper, we present the Knee Point by Minimum Distance Method, which allows us determining a most satisfactory solution from Pareto-set. Optimization result was validated using numerical simulations. Optimal design variables and validated optimization results for the symmetrical and asymmetrical optimization of the head and the tail are shown in Table 2. The total drag coefficient and lift coefficient of head car and tail car of the high-speed train with optimal head shape in symmetrical deformed optimization reduced 0.24%, 3.56% and 9.73% respectively and the optimal head shape in asymmetrical deformed optimization reduced 3.60%, 10.89%, 19.39% respectively compared with the original 0.416, -0.090 and 0.082.

Aerodynamic performance of the optimal train were compared with that of the original high-speed train. Fig. 5 shows comparisons of the pressure contours of the original high speed train, the symmetrical deformed optimal train and the asymmetric deformed optimal train. The air flow slows down when it passes through the nose tip, and the pressure on this region increases rapidly. The maximum positive pressure on the train surface exists in this region. As the flow moves on, a negative pressure region appears on the window of the cab. Similarly, a negative pressure region presents on the cab-window of the tail car with smaller value comparing to the head car. However, the maximum pressure on the tail car occurs near the cab-window and then decreases around the nose tip of the tail car. The pressure distribution patterns of both the symmetrical deformed and asymmetric deformed trains are consistent with the original high-speed train. In the symmetrical deformed optimal results, a positive pressure zone appears at the upper side of the cab-window due to the rotation of the cab-window area, which is more obvious in this situation than the original and asymmetric deformed ones. It can be concluded that the optimization result of the asymmetric deformed high speed train is better than that of the symmetric deformed one as the pressure distribution on the train surface is more uniform and continues.

Simulation results of the symmetrical and asymmetric optimized high-speed train head running in the open air with the speed of 300km/h, 350km/h, 400km/h and 450km/h were compared with the aerodynamic performance of the original high-speed train. Fig. 6 shows the aerodynamic drag coefficient and lift coefficient of the optimal high-speed trains in different speed. It can be seen that the aerodynamic force coefficients tend to decrease with the increase of the train speed. Optimization results of asymmetric deformation is better than the symmetrical deformation as total drag coefficient and lift coefficient of the head car and tail car reduced more in this situation than the symmetrical deformed optimization.
TABLE II. OPTIMIZATION RESULTS.

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<tr>
<th>Type</th>
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<th>Objectives</th>
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<tr>
<td></td>
<td>Cab-window(°)</td>
<td>Nose-length(m)</td>
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<td></td>
<td>Head Tail</td>
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<td>Asymmetrical</td>
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Figure 5. Pressure distribution of the high-speed trains.
(a) Original head (b) Original Tail (c) symmetrical optimal head (d) symmetrical optimal tail (e) asymmetric optimal head (f) asymmetric optimal tail

Figure 6. Aerodynamic force coefficient of the optimal high-speed trains in different speed.

4. CONCLUSIONS

A convenient and efficient approach to the aerodynamic shape optimization of high-speed trains was implemented in this paper. Three design variables of the whole set high-speed train were studied including the angle of cab-window, length of train-nose and width of train-nose. Aerodynamic optimization of the original high-speed train were carried out based on DOE results and the Kriging surrogate model. Optimization results of symmetric deformed and asymmetrical deformed optimization of the head car and tail car were compared. Total drag coefficient and
lift coefficient of head car and tail car of the optimal high-speed train reduced 0.24%, 3.56% and 9.73% in symmetrical deformation and 3.60%, 10.89%, 19.39% in asymmetric deformation comparing with the original ones. Optimization results were validated using CFD simulations. Symmetrical and asymmetric optimized high-speed train head running in the open air with the speed of 300km/h, 350km/h, 400km/h and 450km/h were compared with the aerodynamic performance of the original high-speed train and the aerodynamic force coefficients tend to decrease with the increase of the train speed. It can be concluded that the asymmetric optimization result is better than the symmetrical optimization result.

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REFERENCES