Analysis of Aerodynamics on High-speed Trains

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Abstract. As a matter of fact, the high-speed trains have become an important intercity transportation tool due to their efficiency, safety, and convenience in recent years. However, compared to conventional tree operation at a low velocity, the high-speed railway requires lots of new features. Among different requirement, the aerodynamic behavior of high-speed trains is crucial for their design. With this in mind, this study will briefly introduce the latest progress in the aerodynamic research of high-speed trains based on analysis of principles, simulation results as well as experimental results. To be specific, this study will analyze the train intersection, crosswind effect, tunnel effect, aerodynamic noise, aerodynamic drag, and induced wake, etc. According to the analysis, the current limitations will also be clarified and evaluated. At the same time, the future prospects will be demonstrated and proposed based on the evaluations. Overall, these results shed light on guiding further exploration of high speed trains.

Keywords: High-speed train; train intersection; crosswind effect; aerodynamic noise; aerodynamic drag.

1. Introduction

Due to the rapid development of the economy and the acceleration of social pace, the connection between cities has become closer and closer, and there is an urgent need to develop some fast means of transportation. Efficient, safe and comfortable high-speed trains are the most appropriate choice to meet these needs. According to the recent developing trend, high-speed railways will play a key role in the future transportation system [1-3].

High speed railway (HSR) refers to high-speed train technology designed for operation speed exceeding 250 kilometers per hour, which has high operational safety, comfort, reliability, and economy. The history of high-speed railways can be traced back to the early 1950s, when Europe and Japan began to investigate and develop high-speed train technology. Japan designed and ran the world’s first high-speed train in the 1960s, the so-called Shinkansen, with an operating speed reaching 210 kilometers per hour. Afterwards, Europe and Japan successively built a series of high-speed railways and promoted the progress of high-speed rail technology. As an emerging developing country, China began to develop high-speed train technology until the mid-1990s. In 1998, China successfully put into operation its first “Beijing-Shanghai High-speed Railway” which links Beijing and Shanghai. In 2007, China launched its first trial operation of the China Raiway High-speed Train (CRH) with the designed speed of 350 kilometers per hour, which implies that China’s high-speed railway technology has taken the lead in the world level. China’s high-speed railway system is constantly expanding and has become the world's largest high-speed railway network [4].

As a result of the continuous increase of operating speed, many negligible issues in low-speed operation have become prominent, which has had a significant impact on the operational quality and competitive advantage of HSRs. It is well known that the increase of operating speed results in a significant increase in aerodynamic drag so that it is of great practical importance to diminish the aerodynamic drag to achieve the goal of energy conservation and emission reduction. In addition, the rear of high-speed trains has high turbulence intensity, and the non-linear turbulence generated by the vortex structure near the wake area also requires close attention [5]. Steady aerodynamic characteristics may have adverse effects on people, objects, and the environment within the influence of turbulent wakes, such as when trains run at high speed in dry and sandy areas or when the ballast is not standard (flake ballast, sharp ballast, etc. [6]) it will cause a certain degree of pollution to the surrounding environment and endanger the safety of surrounding personnel, facilities, and equipment

[7-10]. In summary, the improvement of aerodynamic performance and environmental friendliness is crucial in the design of a new generation of high-speed railways, and thus a systematic and comprehensive study of aerodynamic characteristics related to HSRs will play a significant role. This study aims to make a brief summary of the aerodynamic issues: train intersection, crosswind effect, tunnel effect, aerodynamic noise, aerodynamic drag and induced wake, etc., which have attracted intensive attention and investigation by many scholars and engineers.

2. Train Intersection

When a train is traveling at high speed, it will strongly interfere with the surrounding air, so the aerodynamic problems caused by train intersections are very prominent. Note that this disturbance will be intensified as two opposing trains intersect. Particularly when the head or rear of one train goes through another one, it can cause surface swelling on one side of the intersection. The sudden changes in local pressure and the appearance of positive pressure peak and negative pressure peak will cause transient pressure shocks. Bjerklund and Ohman showed that the high-pressure and low-pressure areas at the head of the train have a significant impact on the crossing trains [1]. Due to blocking effect and interference from the movement of another train in the opposite direction, the peak pressure coefficient of two trains intersecting is approximately twice the pressure coefficient of one train running through. Li et al. used the unsteady Reynolds-averaged Navier-Stokes model to describe the three-dimensional slip flow caused by one train or two trains traversing in a tunnel, and carried out a CFD comparative study to verify that the influence of tunnel pressure waves on local airflow is independent of the spatial position of the same cross-section (seen from the Table. 1) [11].

Table 1. Aerodynamic coefficients at different wind speeds

$v_w\ (m/s)$	C_y	C_z	$C_{Mx,lee}(\beta)$
0	0.223	-0.087	-0.287
10	0.339	-0.128	-0.070
15	0.341	-0.130	0.290
20	0.402	-0.144	0.547
25	0.445	-0.158	0.897
30	0.486	-0.170	1.148
35	0.560	-0.213	1.608
40	0.551	-0.236	1.715
45	0.687	-0.292	1.908
50	0.689	-0.282	2.442
55	0.776	-0.332	2.713
60	0.771	-0.338	2.997

3. Crosswind Effect

The aerodynamic load on a high-speed train in strong crosswind has a significant impact on its operational safety. For high-speed train running in crosswind, the free stagnant flow on the windward side surface will produce a high-pressure zone, while the leeward side surface will produce a low-pressure zone owing to the detachment and seperation of a series of large-scale vortices. In addition, when the air traverses the surface at the top of the train at high speed, low-pressure areas will appear, and the pressure difference between these high-pressure and low-pressure areas forces high-speed trains to bear large aerodynamic forces and moments. For this reason, extensive investigations have been conducted on the time-averaged and transient aerodynamic behavior of trains and the surrounding flow structures in crosswind circumstance. Therefore, extensive investigations have been conducted on the time-averaged and transient aerodynamic characteristics as well as the flow structure around the trains in crosswind circumstances (seen from Fig. 1).

Liu studied the aerodynamics of high-speed train running through the transition section of windbreaks through CFD analysis and observed that 1) the aerodynamic performance remains relatively steadly stable when it travels in cuttings and embankments; 2) in crosswind circumstance, the pressure, force and moment coefficients significantly grow, the train exhibits continuous yaw and the front car undergoes the most severe swinging [3]. Muñoz-Paniagua and García utilized genetic algorithms for optimizing aerodynamics of the high-speed train head in two distinct cases where two trains pass by and one train is affected by crosswind, respectively. It has been shown that design variables such as head length, bluntness, and A-pillar roundness have significant impacts in the aerodynamic optimization of the train head [4]. Yu et al. used steady wind model, gust wind model and turbulent wind model to study the crosswind stability evaluation and compared their wind speed time history, force time history and load reduction factor at identical average wind speed. The simulation results illustrate that for various train speeds and averaged wind speeds, the load reduction coefficients and characteristic wind curves (CWCs) of gust model agree with those of turbulent wind model. For steady wind pattern, different assurance coefficients (k) may cause underevaluation or overestimation of CWC [12].

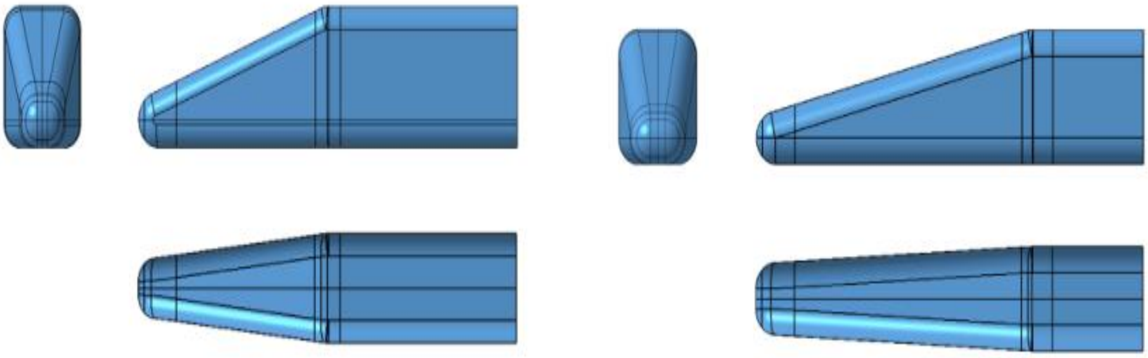

Fig. 1 Comparison between the reference model (left) and the optimized design (right).

4. Aerodynamic Noise

Traction noise, rolling noise, and aerodynamic noise constitute three main sources of noise in high-speed electric locomotives. The traction noise is proportional to operating speed V, and the rolling one is proportional to V^3. However, the aerodynamic noise is caused by the interaction with the airflow, which includes a dipole source with an increase in sound power at a speed of V^6 and a quadrupole source with an increase in sound power at a speed of V^8. Thompson et al. [9] showed that if high-speed trains run at a speed exceeding the critical value (usually around 300km/h or over 350km/h), the aerodynamic noise will dominate over the traction and rolling noises and significantly increase as the speed increases.

The aerodynamic noise originates from pantograph equipment, bogies, train surface cavities, train head and tail, etc. and the level of sound pressure of aeroacoustics gradually decreases according to the pantograph sliding plate, pantograph base, rear of the train, first car bogie, and front of the train. In addition, Talotte and Thompson et al. concluded that when the train reaches a speed of 300 kilometers per hour, the aerodynamic noise generated by the turbulent boundary layer on solid surface does not play a significant role compared to other noise sources. But at higher speeds, boundary layer noise becomes very prominent [8, 9]. Aerodynamic noise can be regarded as a form of energy consumption to a certain extent, so its development trend is often consistent with aerodynamic drag. In other words, reducing aerodynamic resistance is also conducive to reducing aerodynamic noise levels.

5. Aerodynamic Drag

Aerodynamic resistance is an important factor causing energy consumption in high-speed trains. To study the aerodynamic drag, the modified Davis formula

$$F = A + (B_1 + B_2) + CV^2 \tag{1}$$

has been widely used. Here F is the total resistance of train movement, V is the operating speed, A stands for the rolling mechanical drag force, B_1 represents other mechanical resistance (e.g., transmission loss and braking drag), B_2 is the air momentum drag, and the last term is the external aerodynamic drag. For the 350 km/h high-speed CRH3 train consisting of 8 carriages, large-scale parallel computing is used to simulate aerodynamic drag forces and proportions of each component. The pressure difference drags accounts for about 75% of the aerodynamic drag, and the viscous resistance accounts for about 25%. In particular, the head car, tail car, 16 bogies, 2 pantographs, and 7 vehicle end connections account for 16.1%, 15.4%, 26.2%, 12%, and 19.3% of the aerodynamic drag, respectively. To investigate the feature of aerodynamic drag, one focuses on the streamlines of the head and the tail, the lower region of the carriages, bogies, pantographs, and windshields, etc.

5.1. Shape of the Head

The shape of the head seriously affects aerodynamic properties of high-speed trains. It is obvious that train wind produced by the blunt shape of the train nose exerts a greater force on nearby people. In terms of resistance, when the airflow passes through the front nose, a stagnation point is generated to form a high-pressure zone. Meanwhile, the change in cross-section area of the tail result in separation of boundary layer flow along the train body and form a low-pressure zone. The difference of pressure is an important factor of aerodynamic drag. Wind tunnel tests showed that the streamline head with a larger longitudinal slenderness ratio is beneficial for reducing drag. It can be seen that the longitude of the shape has the maximum impact on the aerodynamic behavior, the drag coefficient slowly decreases as the longitude increases, and the aerodynamic coefficient tends to stabilize as it amounts to a certain value.

The optimization results on the head shape illustrate that the longer the head streamline area and the larger the slenderness ratio of the head carriage streamline shape can greatly cut down the aerodynamic drag. However, the effect of reducing aerodynamic drag by increasing the length of the streamline has a limitation, so the streamline portion should not be too long. The aerodynamic performance of single arch head with maximum longitudinal contour line surpasses the double arch one. Trains with a single arch head and a double arch tail have minimum aerodynamic drag, and the head with the maximum convex outer contour line has smaller aerodynamic friction force than that with the maximum concave outer contour line.

5.2. Bottom and Bogie Area

Bogies, wheels, and undercar equipment cause a complex flow of vortices and result in significant aerodynamic drags in the bottom of the carriages, in that area, and the aerodynamic drag caused by the train's bottom structure can account for 53% of the total drag. Therefore, optimizing the structure of the bottom area of the car body and controlling local complex flow is necessary and very effective in reducing aerodynamic drag. Werneg conducted wind tunnel tests on ETR500 train and found that the rectification device of the bogie can cutdown 20% aerodynamic drag [6]. Suzaki et al. pointed out that installing skirts and bogie side covers on the lower part of the car body can effectively reduce aerodynamic drag [7]. Tian discussed the effects of body bottom cover structure, skirt structure, and no bottom cover and no skirt structure on the aerodynamic behaviorand observed that modulus of air drag and lift are small when the car body bottom cover is used, while the air drag is the highest when there is no bottom cover and no skirt structure, and the air drag when using the skirt structure is in the middle [10]. According to the wind tunnel test results, Huang et al. pointed out that in the drag reduction scheme of the body side skirt, the more the skirt covers the exposed part of the bogie, the more conducive to reducing air resistance [2].

5.3. Pantograph Equipment

Japanese scholars have conducted in-depth research on optimization of the aerodynamic performance of pantograph and developed pantographs with low-resistance and low-noise. The straight-arm frame section of the Shinkansen 500 series T-bow adopts a nearly streamlined design, which reduces aerodynamic resistance and noise, while the 700 series high-speed pantograph adopts a single-arm frame, and the joints are designed to be smooth and the air gap is reduced, which improve its aerodynamic behavior. Suzuki et al. studied the influence of two- and three-dimensional pantograph shells with curb panels and box-type pantograph covers on aerodynamic forces [7]. The research results of wind tunnel trial and CFD show that sinking the pantograph and air conditioning system into the roof duct system can reduce aerodynamic drag by 7.5% -12.3%.

5.4. Carriage Compartment Separation

The flow in the carriage compartment is complex, since there are vortices in the upper compartment developed transversely along the train body and local large pressure fluctuations. The fully enclosed windshield can reduce the pressure fluctuations and achieve the purpose of reducing aerodynamic drag [7]. If the ratio of length to height of the train body is large, thick turbulent boundary layers will occur on the top surface and side area. Since the area of entire surface is considerable, the surface friction cannot be ingored. The flow control technology may be used to reduce the superfical frictional resistance. A flow chat is shown in Fig. 2.

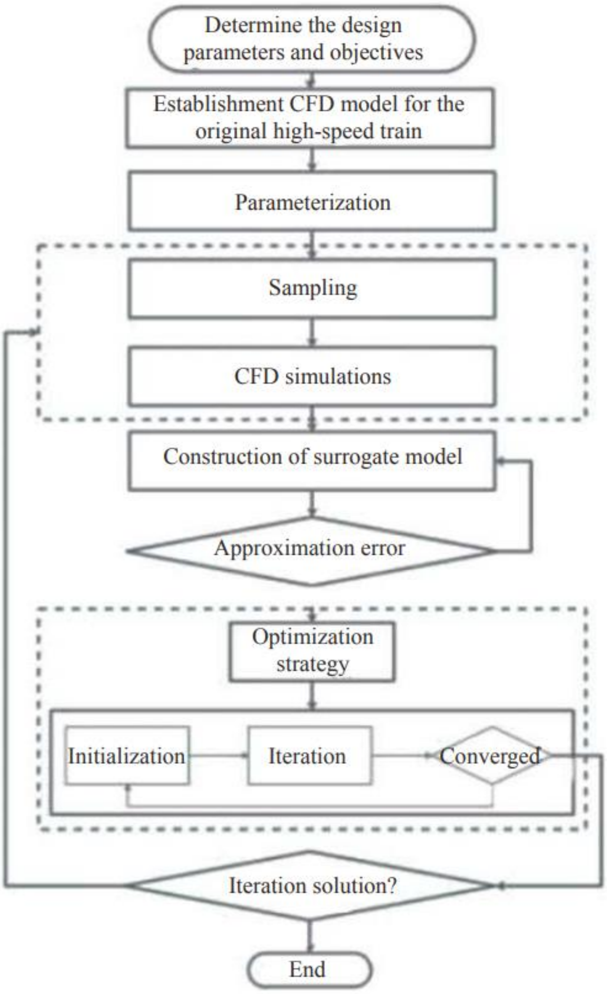

Fig. 2 Different types of InterCityExpress trains and the composition of aerodynamic drag.

Flow control is mainly divided into two categories: active control and passive control. The interface flow control method has been used to delay the separation of boundary layer for drag reduction. The convex and concave structures on the local surface of the front of the carriage can reduce the air drag by 8.16%. Pan used the theory of turbulent boundary layer to study the boundary layer flow on surface and turbulent dynamic process in near wake area which is dominated by large-scale vortex structure [5].

6. Conclusion

The main methods for studying the aerodynamics of high-speed trains consist of numerical simulation method, experimental method (on-site actual vehicle tests, dynamic model tests, and wind tunnel tests), and theoretical analysis. Among them, the numerical simulation method is not affected by the inherent conditions of the experiment and can deeply understand the mechanisms of various flow phenomena or conditions, obtain quantitative results of nonlinear problems, and obtain a large amount of information through calculation during the engineering design process. Numerical simulation methods are becoming an important technique and require further development and improvement.

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