Analysis of the Principle and Applications of Aerodynamics of High-speed Railway

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Abstract. With the advancement of science and technology, the railway has become an important breakthrough. Railroads can transport goods and carry people. Aerodynamics has a huge connection to the study of the high-speed railways. On this basis, the subject of this paper is the principle and application analysis of high-speed railway aerodynamics. To be specific, this study introduces the formulas and principles related to aerodynamics, and how some formulae are used in high-speed railways. The research searches for literature related to railway and aerodynamics and finds the current development status of high-speed railway. The paper explains how aerodynamics affect high-speed rail, the way to transform high-speed railways with aerodynamic knowledge. Contemporarily, there are many methods to carry out the simulation and tunnel experiments. This study also introduces some special experiments to solve special problems about high-speed railway. According to the analysis, there are still many aerodynamic problems that people need to solve, and there is room for improvement in high-speed railways.

Keywords: Aerodynamics; railway; high speed rail.

1. Introduction

Rail is a land-based mode of transportation that transports goods or people. In 2022, the total mileage of global railways will be about 1.1527 million kilometers. Eurasia is the main distribution area of urban rail travel in the world. The total operating mileage accounts for 86.1% of the world. In terms of systems, Asia has the longest subway mileage, accounting for 86.1% of the global subway mileage; North America has the longest light rail mileage, accounting for 40.4% of the global light rail mileage; Europe has the longest tram mileage, accounting for 40.4% of the global tram mileage. 75.4% of the mileage.

The current system of rail transportation is crucial to the sustainable economic growth and providing passengers with access to and from cities. A significant economic hub and has a significant impact on the supply chain. Much of the pressure was released from the public transport and the congestion in the urban areas was reduced [1]. High-speed rail is an important component of the transportation in China. HSR has benefits, including a decrease in greenhouse gas emissions compared to different transportation methods. As a result, HSR revolutionized the travel experience and economic growth of local communities by offering a practical means of transportation, the HSR was a significant advancement towards the country [2]. A high-speed train is a thin train that travels at a high speed on the ground. Because of its large slenderness ratio and proximity to the ground, a variety of aerodynamic issues different from those of aerospace vehicles are present during high-speed operation. These issues primarily include: the drag issue, the crosswind effect, and the meeting place [3]. The turbulent flow around the train is more disruptive because of high speed of trains. As a result, the flow energies become drag, noise and vibrations [4]. Technical status and progress: research on the aerodynamics of high-speed trains at home and abroad in terms of model tests, real vehicle measurements, numerical calculations, etc. [5].

Previous studies describe the development of aerodynamics in China and the world in recent years, and the relationship between aerodynamics and high-speed railways. The literature shows that the study of aerodynamics can reduce the resistance of the air to the high-speed rail to increase the speed, and the study of aerodynamics can ensure the safe driving of the high-speed rail. The literature provides formulas related to aerodynamics. Each part of the high-speed rail suffers from different air resistance, and the resistance is different in different environments, so different formulas are used to calculate the air resistance. Air resistance also has an impact on high-speed rail interiors, such as noise and comfort. The literature introduces the research method of train aerodynamics, and performs numerical simulation calculations through modern technology, so as to simulate the state of high-speed rail in different situations. People get better car body designs. The study will introduce basic descriptions of aerodynamics, principle in high speed railway, simulation and experiment results, limitations and future outlooks of aerodynamics in high speed railway research and conclusion.

2. Basic Description of Aerodynamics

Aerodynamics refers to the examination of the interactions between objects in motion and gases, specifically air. It plays a crucial role in various fields, including aerospace engineering, automotive design, and sports. By understanding the principles of aerodynamics, engineers and designers can optimize the performance and efficiency of vehicles, improve the stability of structures, and enhance the performance of athletes. At its core, aerodynamics involves the analysis of forces and motion in relation to the flow of air. Lift is the force that operates at a right angle to the direction of motion and is accountable for maintaining an object in flight. On the contrary, drag is the force that resists motion and operates in parallel to the airflow direction. Thrust, on the other hand, is the force that propels an object forward. To describe the complex interactions between objects and airflow, several equations are used. The most fundamental equation is the conservation of mass, known as the continuity equation. The principle asserts that the mass of air entering a control volume must be equivalent to the mass of air exiting it. Mathematically, it can be expressed as:

$$\rho 1A1V1 = \rho 2A2V2 \tag{1}$$

Here, ρ1 and ρ2 represent the air densities at two distinct points, A1 and A2 denote the corresponding cross-sectional areas, and V1 and V2 represent the velocities of the airflow at those points. This equation helps determine the velocity and density of the airflow around an object. Another important equation is Bernoulli's principle, which relates the pressure, velocity, additionally, the principle applies to the elevation of a fluid. It indicates that when the velocity of a fluid increases, its pressure decreases, and conversely, when the velocity decreases, the pressure increases. Mathematically, it can be expressed as:

$$P + 0.5\rho V^2 + \rho gh = \text{constant} \tag{2}$$

Here, P represents the pressure, ρ denotes the density of the fluid, V signifies the velocity, g represents the acceleration due to gravity, and h represents the elevation. This principle is crucial in understanding the lift generated by wings and the flow of air around streamlined objects. Here are some additional formulae:

$$\partial\rho/\partial t + \nabla\cdot(\rho V) = 0 \tag{3}$$

$$\rho(\partial V/\partial t + V\cdot\nabla V) = -\nabla P + \mu\nabla^2 V + \rho g \tag{4}$$

$$L = 0.5\rho V^2 ACl \tag{5}$$

$$D = 0.5\rho V^2 ACd \tag{6}$$

3. Principle in High-speed Railway

The application principle of aerodynamics in high-speed railway mainly involves the following aspects. The principle of aerodynamics can be used to study the resistance and aerodynamic force encountered by high-speed trains during operation. By establishing a mathematical model and conducting numerical simulations, it is possible to predict the air resistance encountered by the train at high speed and optimize the shape design of the train to decrease the resistance. The relationship between train running resistance F and train running speed v. The mathematical relationship is F =

C0 + C1v + C2v2. In this: C0 is a constant term; C1 is a linear coefficient; C2 is aerodynamic resistance coefficient; C0+C1v is the mechanical resistance of the train and the cooling of the power equipment. The drag caused by cooling air and vehicle air conditioning; C2v2 is the aerodynamic drag force, including differential pressure resistance and viscous resistance [6].

High-speed trains need to maintain stability during travel. Aerodynamic stability refers to the ability of a train to maintain stability under the influence of air force at high speed. Designers will enhance the aerodynamic stability of the train by modifying the train's shape and center of gravity, as well as installing stabilizers. These measures help to reduce the impact of crosswinds and air vortices on the train at high speeds. The barrier for the wind along the rail is often adversely affected by the aerodynamic forces of the train's wind and cross wind. Its structural integrity is therefore critical. A 1:8 scale simulation of the aerodynamic effect of the train's motion on the energy-dissipating wind barrier in the chamber is conducted using the dynamic platform of the high-speed train. When different types of trains pass through the wind barrier area at different speeds, the aerodynamic pressure at different locations within the wind barrier is evaluated. The variation of the aerodynamic pressure is studied [7].

High-speed trains will generate a large number of airflow and air pressure changes during travel. To ensure comfort and safety inside the train, designers need to consider the train's ventilation system. The ventilation system can maintain the proper temperature and humidity by controlling the airflow inside and outside the train and remove harmful gases and smoke inside the train. In addition, the ventilation system can also help reduce air pressure changes inside the train to provide passengers with a comfortable ride. The researchers established an analysis model of the high-speed train ventilation system built upon the one-dimensional simulation software Flowmaster. The system conducts one-dimensional modeling and analyzes dynamic pressure fluctuations and proposes an optimization scheme for the ventilation system; it solves the problem of the impact of transient pressure fluctuations outside the train on the comfort of people inside the train [8].

4. Simulation and Experiments

Numerical simulation is to numerically solve the air flow around the rail train by computational fluid dynamics method. This method can obtain parameters by establishing the geometric model and motion conditions and solving the flow equation by numerical methods. Numerical simulation methods can provide detailed flow field information and aerodynamic force distribution to comprehensively evaluate the aerodynamic performance of high-speed trains. Experimental testing is to obtain parameters by testing trains in wind tunnels or in actual operating environments. In the wind tunnel experiment, a scaled-down high-speed train model can be used to simulate different airflow conditions by modifying the wind speed and airflow direction within the wind tunnel. The aerodynamic performance can be evaluated by measuring parameters such as pressure distribution, drag, and lift on the surface of the model. In the wind tunnel test, researchers investigate the impact of railway wind barriers on the distribution of wind pressure above the track. Researchers firstly conducted CFD simulations for typical wind tunnel test conditions and compared the results of the wind tunnel test with the CFD simulation results [9].

Ballast is produced by train power and aerodynamic force, and the phenomenon is that the ballast on the surface of the track bed migrates, jumps or even flies away track bed, and hit the train body and bogie. It generally occurs when the speed exceeds 300 km/h and is very harmful. The author of the literature studies the aerodynamic characteristics of the ballast track through the ballast track wind tunnel test and aerodynamic simulation. The 350km/h high-speed rail driving in this experiment provides a reference. Since the wind speed reaches 30 m/s when the vehicle speed increases to 350 km/h, the authors use the monitor to record the wind pressure data when the wind speed increases from 3 m/s to 30 m/s, and compare it with the simulated data. To learn about the movement law of ballast under the action of wind load, experiments, experimental models and results are carried out. According to the previous analysis, the negative wind pressure in the center of the ballast bed is relatively large, the wind speed is high, and it is relatively stable [10, 11]. The wind pressure on the ballast shoulder rises with the increase of the pile height of the ballast shoulder (seen from Fig. 1) [11]. Reducing the elevation of the bed's topography does not have a substantial impact on the wind strength field, but it can decrease the risk of the bed's sleeper falling onto the surface. The particles of the ballast initially vibrate. Then they roll underneath the wind load. The particles at the center of the track, the surface of the sleeper and the ballast's shoulder are more likely to move.

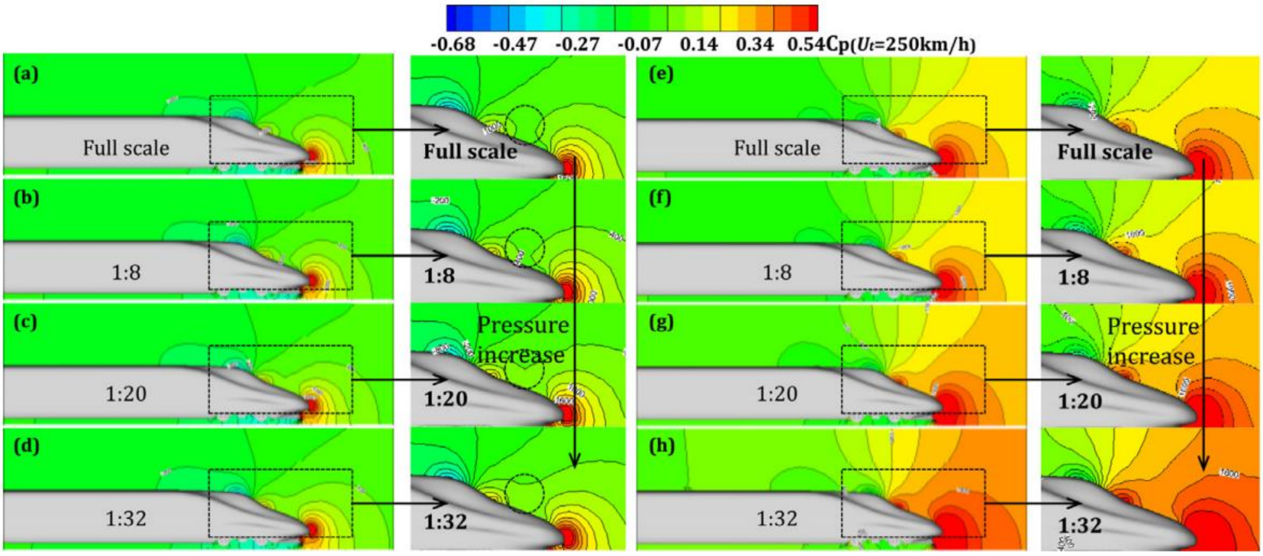

Fig. 1 A sketch of pressure simulation.

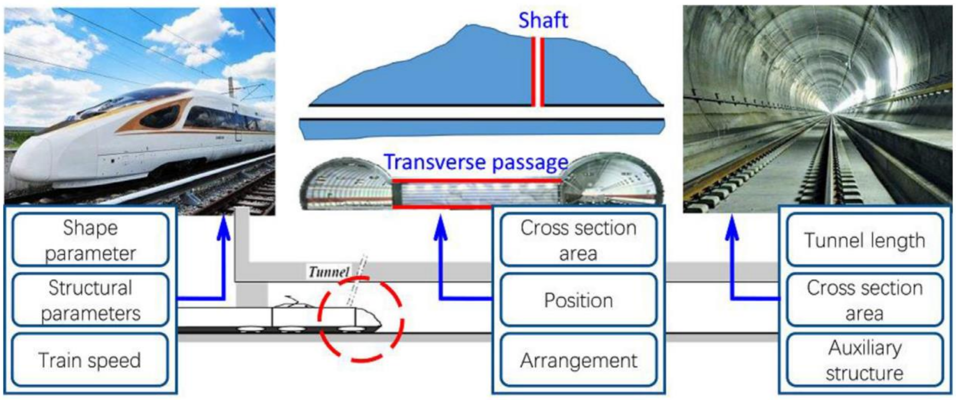

Fig. 2 Aerodynamic influencing factors for railway.

5. Applications

The Fig. 2 lists the aerodynamic influencing factors for railway. The streamlined shape can reduce air resistance. The streamlined shape can make the air flow more smoothly on the surface of the object and reduce the generation of resistance. For example, high-speed trains, cars, and airplanes are often designed with streamlined shapes to reduce air resistance. By reducing the projected area of the object in the air, the drag effect of the air on the object can be reduced. Take a case, the front of a train is usually narrower to reduce the cross-sectional area of the front, thereby reducing air resistance. Smooth surface design can reduce air resistance. A smooth surface can reduce the frictional resistance of air on the surface of the object, thereby reducing the overall air resistance. In aerospace and automotive designs, smooth coatings and special surface treatments can be used to reduce air resistance. To reduce the aerodynamic drag and facilitate faster train operation, tubes were evacuated. As a new form of rail travel, the aerodynamic properties of the evacuated train are affected by the internal pressure of the train, the blockage ratio, and the speed of the train, when the train reaches a critical speed, shock waves will appear in the train's tube [11].

High-speed trains will be affected by crosswinds during travel, which may lead to train instability. Through aerodynamic research, the shape design of the train can be optimized to reduce the impact of crosswinds on the train. For example, by changing the shape of the train body, reducing the projected area of the side, and adding crosswind stabilizing devices, the force of the crosswind on the train can be reduced and the stability of the train can be improved. Aerodynamic studies can help in the design of train body and suspension systems to control the distribution of aerodynamic forces. By rationally designing the shape of the front and rear ends of the car body and the aerodynamic device at the bottom, the distribution of lift and resistance on the train can be adjusted, thereby improving the stability of the train. High-speed trains may encounter aerodynamic oscillations when running at high speeds, such as the oscillation of aerodynamic forces and the generation of vortices. Through aerodynamic research, the shape and body structure of the train can be optimized to reduce the occurrence of aerodynamic oscillations. For example, by increasing the rigidity of the car body and adopting measures such as damping devices, the aerodynamic vibration of the train can be reduced and the stability of the train can be improved. Aerodynamic forces experienced by vehicles in an adverse environment are primarily determined through wind tunnel experiments. Early investigations often employed simple assessments that utilized wind that was blowing at a uniform rate on to intermediate vehicles at the ground level. Today, evaluations replicate the three-dimensional shape of the car's body, including the leading vehicle and the ground structure, such as bridges and embankments, they also utilize an airflow field that resembles the distribution of natural wind's average velocity and intensity [12].

6. Limitations & Future Outlooks

When a train runs at high speed, it will generate aerodynamic noise, which will bring discomfort to the surrounding environment and passengers. Although some measures have been taken to reduce noise, such as improving the body shape and shock absorbers, further research is still needed to solve this problem. In addition, when high-speed trains pass through special terrains such as tunnels and bridges, changes in the aerodynamic effect will occur, which may affect the stability and safety of the train. Current research focuses on simulating and predicting these effects so that adjustments and improvements can be made during the design and construction phases. The aerodynamic research of high-speed railway still faces the constraints of experimental conditions. Since the high speed of high-speed trains, the experimental conditions are difficult to simulate the real operating environment. Therefore, researchers often need to rely on methods such as numerical simulation and computational fluid dynamics to conduct research, which may lead to certain errors and uncertainties.

Current, people can expect the following developments: First, researchers will continue to work on minimizing the aerodynamic resistance of high-speed trains. By improving the shape of the car body, optimizing the structure of the car and reducing air resistance, the operating efficiency and energy utilization of the train can be further improved. In addition, the researchers will also focus on the aerodynamic effects in special terrain. By simulating and predicting these effects, the stability and safety of the train can be optimized to make sure the train operates smoothly in diverse terrain conditions. Moreover, methods such as numerical simulation and computational fluid dynamics will be more widely used. This will allow researchers to more accurately simulate and predict the aerodynamic behavior of high-speed trains, providing a more reliable basis for design and optimization. Finally, with the continuous expansion and renewal of the high-speed railway network, aerodynamic research will be combined with research in other fields, such as material science, energy technology, and intelligent control. This will boost the overall performance of the high-speed rail system for more efficient, safe and environmentally friendly operation.

7. Conclusion

To sum up, this study is about the dynamic's principle and application analysis of high-speed aerial railway. With the advancement of science and technology, railway has become an important starting point, a hot research area in the interaction between railway transportation system and air flow. Related theories, improve the performance of the train by changing the appearance design of the train, reducing air resistance, optimizing the car body structure and reducing noise. However, the current aerodynamic appearance design, such as the numerical value simulated by technology, deviates from the actual situation. In the future, it is hoped that the field of aerodynamics can be studied more thoroughly. By studying aerodynamics, engineers strive to create efficient, safe, and sustainable railway systems that contribute to the advancement of transportation technology.

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