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Research on Head Shape Optimization of High-speed Trains Based on Multifactor ANOVA and Streamlined Head Optimization CST Methods

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Abstract: *This paper explores the optimization of high-speed train shapes, focusing on reducing wind resistance and noise. A multi-factor ANOVA model and streamlined head optimization CST method are used to analyze structural parameters. The study first establishes a wind resistance model, selecting the TP1-type high-speed railway for its minimal air resistance. The paper then optimizes the train head shape, identifying the warhead structure as optimal for aerodynamics. Additionally, it examines noise reduction in locomotive heads, finding the platypus-shaped TP4 type most effective. Finally, the results culminate in a comprehensive optimization model for the train head shape, providing an optimal design sketch with structural parameters.*

Keywords: *High-Speed Train Design, Aerodynamics, Wind Resistance, Noise Reduction*

1. Introduction

In the high-speed rail sector, the advent of trains capable of maintaining speeds exceeding 300 km/h symbolizes a significant leap in railway technology, offering enhanced travel speed and comfort. Such high-speed trains have attracted worldwide attention due to their exemplary stability, safety, energy efficiency, and environmental benefits. Optimizing the design of these trains is crucial, focusing on their shape, speed, comfort, noise reduction, and cost-effective material usage. This paper delves into finding the optimal design strategies for high-speed trains, grounded in aerodynamic principles, and supported by extensive simulations and tests. The research involves developing models to evaluate the impact of air resistance on trains, the interplay between the trains' geometric shapes and various atmospheric conditions, and the effect of track curvature on air resistance. Additionally, it includes establishing a mathematical model for noise assessment in railways, particularly considering the noise emanating from the trains' conical front ends and simulating noise distribution for different track head structures. The culmination of this study is a comprehensive model that integrates the findings to propose an optimal shape for high-speed trains. This model aims to enhance train speed, economize on materials, improve aesthetic appeal, reduce weight, and minimize noise, thereby presenting an efficient, cost-effective, and environmentally sustainable solution for high-speed train design [1].

2. Air resistance and shape optimization of high-speed trains

2.1 Mathematical model of air resistance in high-speed rail

TP1, TP2It is a Chinese train locomotive with a bullet structure, and TP3 and TP4 are Japanese train locomotive structures with a platypus structure. Among them, the design of the train head structure considers wind resistance and noise level, and Fig. 1 below is a simplified model of four typical high-speed railway head structures.

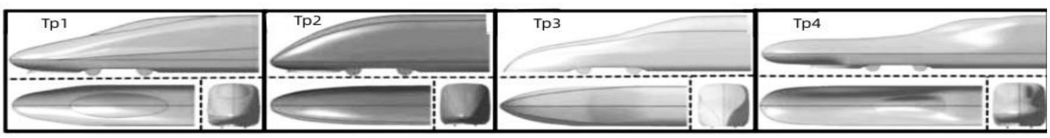

Figure 1: Simplified models of four typical high-speed rail head structures

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In this study, the new-generation standard Electric Multiple Unit (EMU) "Fu Xing," independently developed by China with full intellectual property rights, serves as a primary example to explore high-speed train design focusing on wind resistance and noise levels. Utilizing fluent simulation software, this paper successfully captures the air pressure distribution cloud of four typical high-speed railway track heads and their surroundings at a speed of 200 km/h. This approach aids in visualizing the aerodynamic characteristics of various high-speed train designs, crucial for optimizing their performance.

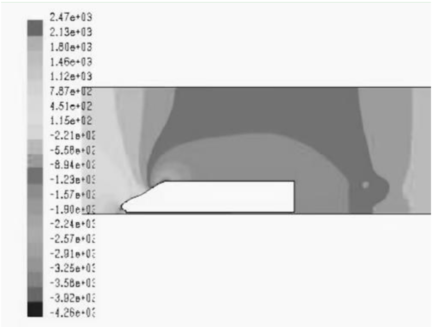

Figure 2: TP1 air pressure distribution cloud

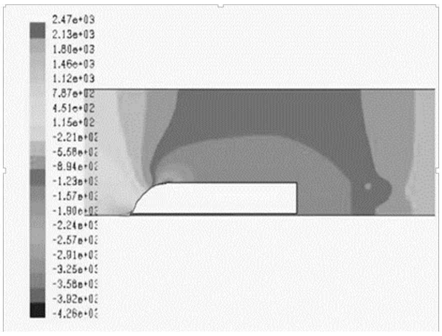

Figure 3: TP2 air pressure distribution cloud

Figure 4: TP3 air pressure distribution diagram

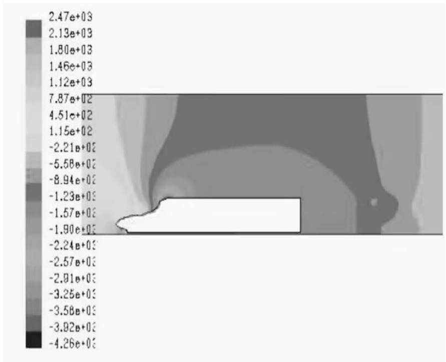

Figure 5: TP4 air pressure distribution diagram

In Fig. 2 to 5, an in-depth analysis of the aerodynamic optimization of high-speed trains is conducted, with a particular focus on the air resistance coefficients of various train head shapes. The analysis includes the conical shape and four typical high-speed railway track head shapes, all examined under the same operational conditions. The key finding from this analysis is the variation in air resistance coefficients across different models. For example, the TP1 model shows a notably lower air resistance coefficient compared to the TP2, TP3, and TP4 models, which indicates a significant difference in aerodynamic efficiency among these designs. All models were evaluated at a uniform speed of 435 km/h, providing a consistent basis for comparison [2].

This study conducts a detailed investigation into the aerodynamic performance of high-speed trains, with a particular emphasis on comparing the bullet and platypus head designs. The research concludes that the bullet structure significantly outperforms the platypus head in terms of aerodynamic efficiency. This finding is critical as it highlights the profound influence of train shape on the running resistance of high-speed trains and railways. The study advocates for design strategies that avoid abrupt changes in surface curvature, recommending a bullet-shaped locomotive for its superior streamlined characteristics. These conclusions are derived from a comprehensive methodological approach, encompassing vehicle aerodynamic tests, model simulations, wind tunnel experiments, dynamic modeling, and numerical simulations. These methods collectively facilitate a nuanced understanding of aerodynamic properties under varying weather conditions. In Table 1, by applying specific wind power values from different weather scenarios to the aerodynamic models, the research identifies the TP1 shape as the most aerodynamically efficient design. This key result provides a vital insight into optimizing the design of high-speed trains, aiming to enhance efficiency and reduce environmental impact in the realm of modern railway transportation [3].

Table 1: Wind level, wind speed and train relative speedometer

Wind Level	No wind	Soft wind	Breeze	Zephyr	Strong wind	Gale	Blast
Wind Velocity M/s	0.0-0.2	0.3- 1.5	3.4-5.4	5.5-7.9	8.0- 10.7	10.8- 13.8	13.9- 17.1
Vs	339.88	338.5	334.6	332.1	329.3	326.2	322.9

2.2 Optimize the model with the shape of the train locomotive.

In recent years, with the continuous increase of the driving speed of this high- speed train high-speed railway, the resistance of high-speed train high-speed railway is also increased, resulting in increasing energy consumption, and there will be an instantaneous change in air pressure, resulting in excessive deformation of the side wall of high-speed train high-speed railway. In addition to high-speed trains, the structural design of high-speed railway locomotives considers wind resistance. High-speed train is the main direction of China's railway technology development, so the research and development of the shape of the head of the high-speed train is the most important part, the train head not only affects the aesthetic effect of the whole train but also affects the resistance of operation and the safety and stability of the train operation. Through the development history of foreign high-speed trains and high-speed railways, it can be clearly known that each update of high-speed trains and high-speed railways will improve and adjust the shape of the train head. Therefore, aerodynamic problems have become a key technology that must be studied and solved in modern high-speed trains, and the research results of aerodynamics will be fully demonstrated in the development of a new generation of high-speed trains and high-speed lines. Therefore, we can build a mathematical model of the air resistance of high-speed railways with the help of general formulas of air resistance and editing and calculation through computer programs.

$$F = \frac{1}{2} C_X \rho s v_s{}^2 \tag{1}$$

The research focuses on the optimization of high-speed train design, particularly in terms of aerodynamics. Central to this optimization is the analysis of the train's length and slenderness ratio, which are crucial factors in determining the most efficient shape for reducing air resistance. The study employs an analytical approach that considers the balance between the train's length and its cross-sectional profile, aiming to achieve a design that minimizes wind resistance while maintaining structural integrity and aesthetic appeal.

The methodology of the research includes the application of the least squares regression method. This statistical approach is used to establish an empirical regression equation, a key tool in correlating various design parameters with aerodynamic efficiency. By graphically representing these relationships through a regression line, the study provides insights into the optimal design parameters that contribute to the aerodynamic performance of high-speed trains [4].

Furthermore, the research involves the development of an air resistance model. This model is essential for a comprehensive understanding of the factors affecting the aerodynamics of high-speed trains, such as air density and velocity. The model is supported by empirical data, which includes measurements and statistical information, ensuring the accuracy and validity of the research findings.

Additionally, the study manages the conversion of curve radians to angles with meticulous diligence. This aspect is critical for the precision of aerodynamic calculations, ensuring that all measurements and transformations are accurate and conducive to developing a dependable aerodynamic model.

Overall, this research contributes to the field of high-speed train design by offering an in-depth analysis of aerodynamic factors and proposing optimized design solutions. The findings of the study are expected to have significant implications for the development of more efficient, safer, and aesthetically pleasing high-speed trains.

Through the calculation of a computer program, the shape optimization model of high-speed train and high-speed railway is applied, and the curve curvature of the locomotives of high-speed train and high-speed railway is combined with the influence of air resistance factors on the high-speed train and high-speed railway model, and finally the longitudinal section and transverse section optimization shape sketch of the above Fig. 6 and 7.

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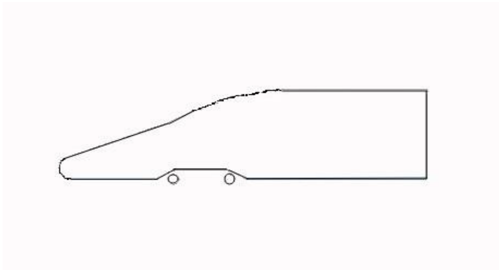

Figure 6: Sketch of the optimized longitudinal cross-sectional shape of high-speed rail

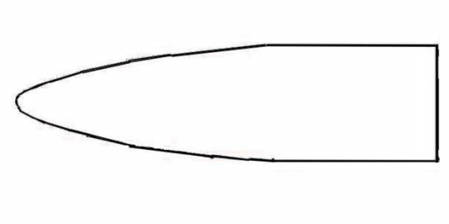

Figure 7: Sketch of the optimized transverse section shape of the high-speed rail

3. Integrated noise control and train head shape optimization

3.1 Mathematical model of high-speed rail noise

Taking TP1 as an example, the high-efficiency mesh is the key to improving the calculation accuracy of the transient flow field and aerodynamic noise on the surface of the nose. The structural mesh generated by applying the mapping method is not only computationally efficient but also artfully arranged, which is a very ideal meshing method [5].

The steps of the mapping method to generate a structured quadrilateral mesh are: map the physical domain to be split into the parameter space through the mapping function to form a regular parameter domain; Mesh the rule parameter domain; The mesh of the parameter domain is mapped back to the physical space to obtain the numerical mesh of the physical domain.

According to the mapping method, the quadrilateral skin mesh of the head of the high-speed train is generated. The complex high-speed train shape output by the three-dimensional modeling software is used as the mapping reference. The quadrilateral grid is mapped to the surface of the streamlined shape of the high-speed train, which cannot simplify the streamlined shape in any way, and the grid divided is unconventional. Based on the generated quadrilateral mesh of the surface of the high-speed train, it is extremely easy to form a hexahedral mesh for flow field calculation. This mesh generation method is easy to parameterize, the selection of calculation area, and the adjustment of grid density only need to assign different values to each parameter in the initial part of the program. After the mesh is generated, the program can automatically input it into any mainstream CFD software for numerical calculations of high-speed train aerodynamics. The optimal high-speed railroad shape surface network is shown in Fig. 8.

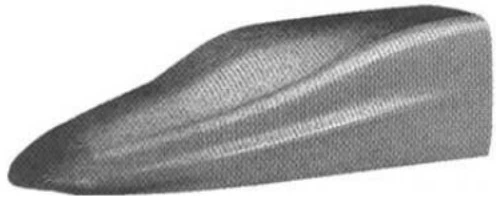

Figure 8: Optimal high-speed rail shape surface network diagram

In this part, a detailed discussion is conducted on the calculation methods for the Light hill wave equation and static flow. A separate wave equation is introduced to solve the transmission of Light hill pressure, which is expressed as the sum of acoustic pressure and hydrodynamic pressure. The transmission equation for Light hill pressure is further defined, and the paper delves into the composition of Light hill pressure as the sum of the fluid dynamic fluctuating pressure and sound pressure.

Additionally, the paper analyzes the signal base wood theory of moving train arrays and establishes the geometric model of moving sound source points and measurement points.

Addressing the conventional motion sound source recognition method, this paper proposes a sound source measurement method based on a non-simplified model. By employing calculus, a mathematical model of motion sound source that eliminates the Doppler effect is established, characterized as a non-destructive accuracy mathematical model. The paper also derives the sound field reconstruction formula of motion sound source beamforming based on the non-simplified model. To maximize the system's anti-interference ability and improve the accuracy of the system's sound source pointing the decorrelation term method is utilized to reduce noise, especially in selecting four typical simplified models of high-speed rail head structures.

$$p^l \quad p^a \quad p^h \tag{2}$$

$$h = \nabla[bs\,\rho(v ※ v - v ※ v)] \tag{3}$$

Therefore, through the comparison of data and simulated noise distribution, a mathematical model of high-speed rail noise is established, and then a precise comparison is carried out, and the head structure of high-speed railway with platypus type (TP4) as the high-speed train is the shape of high-speed rail with the least noise and the best effect.

3.2 The CST method is optimized based on air resistance and noise intensity streamline.

Based on the characteristics of the streamlined head type, the CST method is applied. The key design parameter values in the shape function and category function are accurately known. The optimized CST method is established based on the idea of optimization fitting to make the head shape fitted by the CST method closer to the actual train head type [6].

Based on the first three problems, we establish a comprehensive optimization model of the locomotive of the high-speed train and high-speed railway and design the optimal shape of the train locomotive, which can also improve the speed of the high-speed train and reduce the noise of the high-speed train and high-speed railway.

A three-dimensional shape can be seen as a series of parallel cross-sections along the axis. By using shape functions to describe different cross-sectional shapes at different axial positions, an analytic shape function surface is determined, to obtain the analytic description form of the entire three-dimensional shape.

The above defines the complete analytical description rules for 3D parametric geometric surfaces, and the normalized 3D CST surface expression can be obtained by converting the above definition into the physically meaningful Cartesian global coordinate system. Combined with the characteristics of the complete opening of the rear of the real train streamline head, M2 and T2 should be 0 in the exponent of the class function; In addition, the real locomotive head shape is symmetrical left and right along the middle symmetry plane, so the indices N1 and N2 should be equal, and the elements of the rows of the weight coefficient matrix by are also symmetrical. At the same time, to further reduce the number of design variables, the order of the shape function specified in the three dimensions during the parameterization process is third order. In the design process, a comprehensive optimization model of a reasonable train locomotive should be used through analysis and calculation. The optimal shape of the train locomotive was designed as shown in the Fig. 9 and 10:

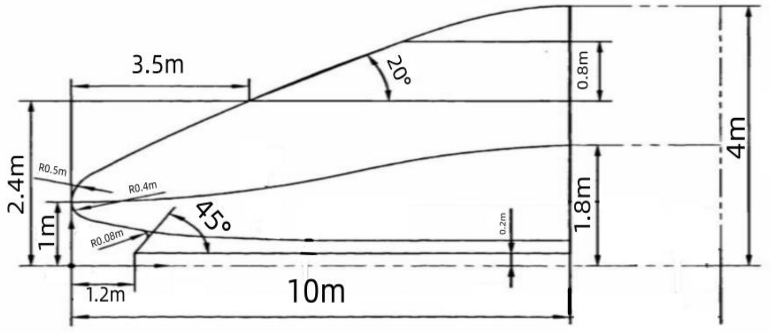

Figure 9: Sketch picture of the side shape of the train locomotive

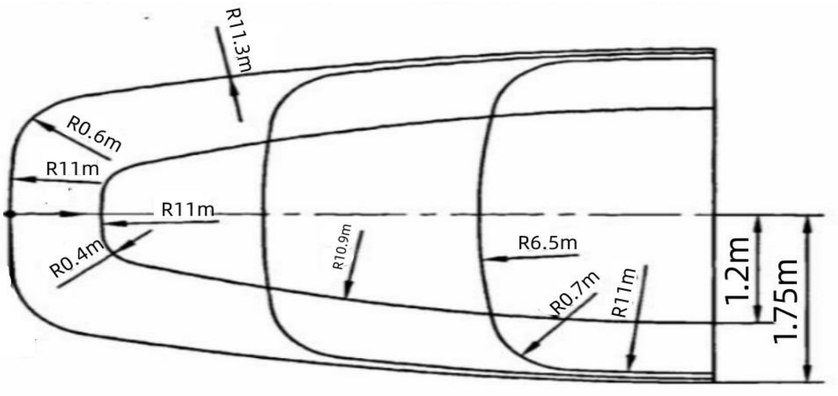

Figure 10: Sketch drawing of the cross-section shape of the train locomotive

4. Conclusions

This paper presents a comprehensive optimization model that integrates aerodynamics theory, focusing on air resistance, high-speed rail shape optimization, and noise reduction for high-speed trains. Utilizing multiple linear regression equations and scientific methods such as the least squares method and the doppler effect, the model simulates and analyzes various uncertain factors based on aerodynamic formulas, Light hill wave equations, and standard k-epsilon model equations. Despite its strengths, the model has limitations, including insufficient data and a lack of detail in considering factors, leading to potential errors and cumbersome computer program operations. To enhance the model, optimization of computer algorithms and deeper research into design and data are suggested, aiming to align the model more closely with real-world dynamics. Overall, the model effectively addresses the challenges in the optimal design of high-speed train locomotives, backed by robust data and literature. It offers practical solutions that are adaptable to real-life scenarios, with a high degree of data accuracy and applicability in generalizing the findings.

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