Research on Aerodynamic Shape Design of Wings of Hypersonic Aircrafts

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Abstract. One of the primary fields of aerospace study is aerodynamic profile design. Most of the current research focuses on the design of subsonic aircraft, but there is a gap in hypersonic aircraft. As a result, the aerodynamic configuration of hypersonic vehicles is the subject of this paper. The researchers discovered the foundation, trend, and expansion of the current aerodynamic configuration research of each part by introducing the aerodynamic optimization methods of the four airplane parts. The research results show that multi-scientific collaborative design utilizing numerical methodologies and the integration approach of individual component designs is required for the fuselage. While the wing portion can raise the aircraft's development quality through optimization design simulation, the "blunt head" of the bow can still be optimized to increase safety and save costs. The wing component can enhance the calibre of aircraft development using design simulation and optimization. Therefore, the design of hypersonic vehicles relies on precise and effective algorithms and numerical models. The purpose of this study is to explore and fill the gap in the hypersonic aerodynamic design of aircraft, to optimize the design scheme under the condition of low cost and high efficiency.

Keywords: Hypersonic vehicle, Aerodynamic, Profile design.

1 Introduction

Hypersonic vehicles are generally defined as vehicles travelling at Mach numbers greater than 5, in the atmosphere [1]. Good aerodynamic shape design can greatly improve the aircraft stability and fuel efficiency of the vehicle. Therefore, aerodynamic shape design is one of the issues that have been a concern in the aerospace field.

In the research process of this paper, it is found that the difficulty of hypersonic vehicle aerodynamic design lies in how to balance the various components of the hypersonic vehicle to maintain good control and stability under flight conditions. At the same time, as the flight Mach number of hypersonic vehicles continues to

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increase, the connection between various disciplines is also enhanced, which makes the difficulty of hypersonic design also increase. The aerodynamic principle of a hypersonic vehicle, as the basis of its design, involves several aspects, including the optimisation of the aerodynamic layout of the vehicle, the improvement of the design of the mathematical controllable model, and the aerodynamic shape design of each part of the vehicle, etc. The aerodynamic principle of the hypersonic vehicle is the basis of its design, which involves several aspects. Among them, the main purpose of hypersonic vehicle aerodynamic layout optimisation is to increase the lift and reduce the drag design, which makes the researchers often need to consider the lift symmetry shape of the same aircraft, to meet the loading requirements, thermal protection requirements, controllability requirements, etc. of the hypersonic vehicle. At the same time, it is also crucial for researchers to control different mathematical calculations for hypersonic vehicles. Through various types of mathematical models, the researcher can effectively understand the state of the vehicle under different flight conditions to optimise the vehicle. On the other hand, researchers have been continuously studying the aerodynamic optimal design of each flight unit of hypersonic aircraft, taking the research on the aerodynamic shape optimisation design of a single part - the wing as an example, there are the Kriging agent model approach [2], Kriging Agent Model method, Generative Adversarial Network method [3] Class Shape Function Transformation [4]. However, there is no systematic review of the aerodynamic optimal layout of hypersonic vehicles.

The main purpose of this paper is to organise the research methods for the various parts of hypersonic vehicles with a short introduction and side-by-side comparison. Finally, a developmental summary of the aerodynamic profile optimisation methods for each part of the hypersonic vehicle is presented.

2 Influence of Hypersonic Aircraft Shape on Its Aerodynamic Performance

2.1 Airframe Status of Pneumatic Research

Hypersonic vehicles mainly include three categories: hypersonic cruise missiles, hypersonic aircraft, and space shuttles, and the hypersonic vehicle fuselage is an important part of it, which is characterised by lightweight, high strength, streamlined design, and stable structure. Its fuselage usually consists of using truss structure, as shown in Figure 1: intake pipe, supercharger, combustion chamber, turbine, tail nozzle, and so on. The above components are also the important direction of the current research on the aerodynamic shape optimisation of hypersonic aircraft fuselage [5].

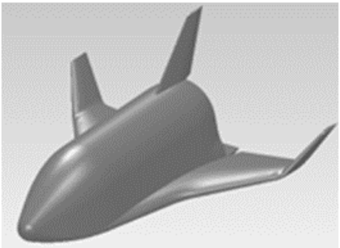


Figure 1. Hypersonic aircraft fuselage three-dimensional structural schematic [6].

In the study of hypersonic vehicles, the optimised design of the DLR-F6 aircraft profile was carried out by using the Hick-Hene method for the fuselage short compartment [7], which generated different component design variables. Based on these different design variables and the coherent line profile, the pressure coefficients were analysed by interpolation. The results of the two optimised designs are shown in Table 1 [7], which show that the difference calculation method using correlation lines aligned to adjacent component surfaces is beneficial to the simple aerodynamic airframe optimisation design method. Hu et al. [8] investigated the influence of leading-edge fuselage on the performance of force resistance. The lift and drag parameters of each part of the fuselage were obtained and analysed using a modified method and numerical simulation. The results are shown in Figures 2 and 3 [8], whose study shows that choosing only a single fuselage shape parameterization for the aerodynamic layout of the fuselage fusion body can obtain a more accurate proportional value of the impact of lift drag. Comparing the two studies, both use various types of numerical calculation methods and parametric analyses. The focus on the aerodynamic design of the fuselage is not the same. The former [7] focuses more on the air pressure analysis of a single fuselage component, while the latter [8] focuses more on the lift and drag analysis of a single fuselage shape.

Therefore, the aerodynamic research of the fuselage part of the hypersonic vehicle has implied that the aerodynamic research of the fuselage needs multi-scientific co-design since it was proposed, and the design numerical method and the strategy of integrating the design of each component is an effective way to solve the aerodynamic direction of the fuselage.

Table 1. Optimisation design results [7].

	C1	C4
Initial shape	0.50	0.01831
Optimisation 1	0.50	0.01689
Optimisation 2	0.50	0.01678

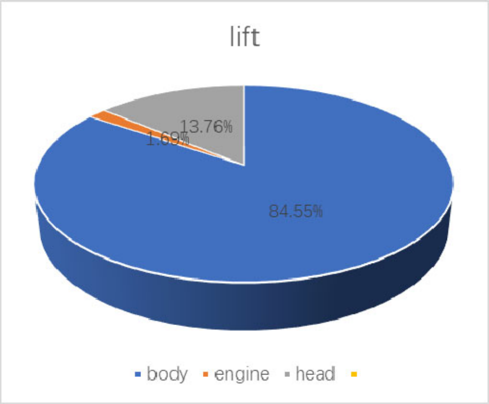


Figure 2. Proportional values of lift for each airframe section (Photo/Picture credit: Original)

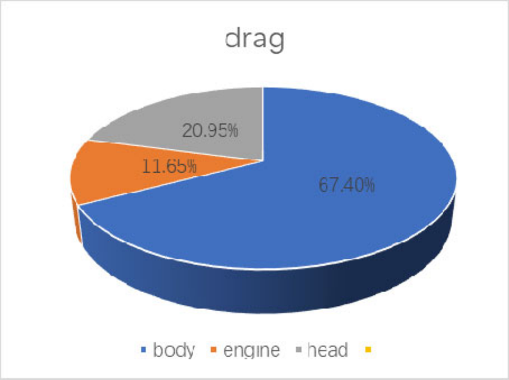


Figure 3. Proportional values of drag for each airframe section (Photo/Picture credit: Original)

2.2 Bow of the Aircraft's Status of Pneumatic Research

When a hypersonic vehicle flies in a dense atmospheric fluid, the intense friction between the airframe and the air leads to a significant increase in the temperature of the skin of the vehicle and the occurrence of the thermal barrier phenomenon. The bow of the aircraft accumulates a large amount of heat, which seriously affects the structural strength of the bow of the aircraft. It is very important to predict the performance of hypersonic vehicles before flying, and Zhang et al［9］proposes a coupled calculation method integrating aerodynamic heat, material erosion, and transient temperature field, and realises the calculation of material erosion caused by high temperatures and the analysis of temperature environment in the flight of hypersonic aircraft through a numerical example. Regarding the aerodynamic heat calculation, the Fay-Riddell formula is used for the engineering calculation method of the standing point heat flow. The Lee’s simplified formula is used for the calculation of the heat flow density on the surface of the ball head. The high silica/phenolic material used in this numerical example is a typical silicone-based material for material ablation calculations as shown in Figure 4 [9].

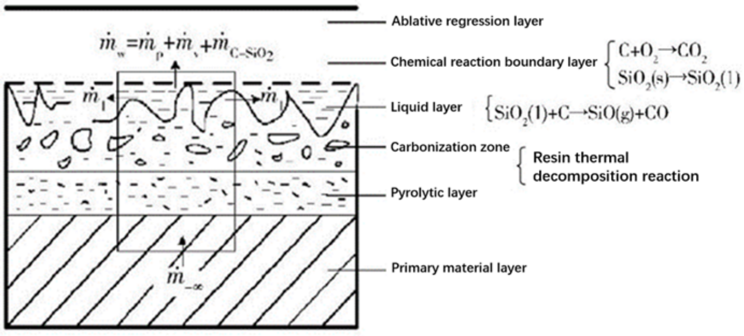


Figure 4. Ablation modelling of high silica/phenolic composites [9].

In the calculation of the temperature field of multi-layer materials, i.e., the one-dimensional unsteady thermal conductivity equation, the solution region is discretized, as shown in Figure 5 [9].

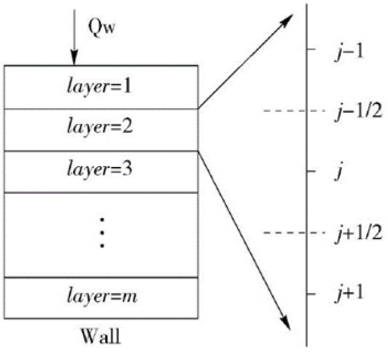


Figure 5. Multilayer material discrete [9].

Previous studies tended to add head-opposed jets to reduce the aerodynamic heating of hypersonic aircraft with blunt-shape heads. The current research interest is mainly focused on the aerodynamic heating of hypersonic aircraft under single and defined free-incidence conditions only. The current research interest mainly focuses on the reduction of surface heat from opposite jets under single and deterministic free incidence conditions, rather than in the presence of free flow disturbances. Zhang et al ［10］ designed the Polynomial Chaos method to quantify the surface thermal uncertainty in the inner layer, including the mean value and the standard deviation, under free incoming perturbations. At the same time, they designed the Variance Analysis method to describe the jet geometry and flow parameters on surface thermal uncertainty in the outer layer.

Figure 6 shows the baseline geometry of the blunt-shape heads of the general hypersonic aircraft [10].

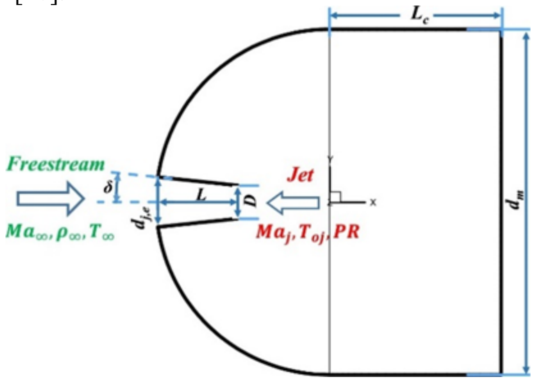
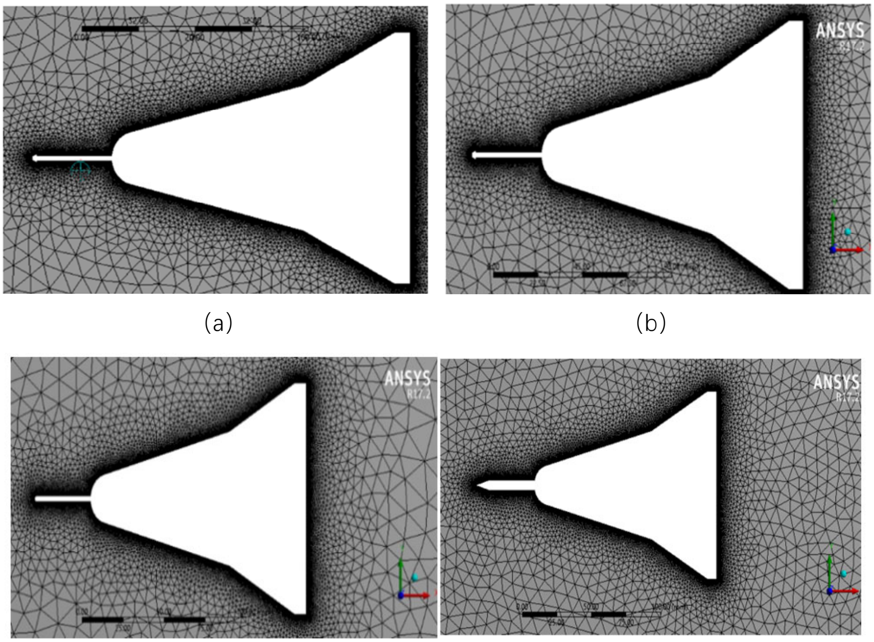


Figure 6. Baseline geometry of the bow [10].

Panjagala et al. [11] introduced different shapes of spikes at the frontal region of the nose to reduce the heat generated in the nose of the aircraft by the friction between the aircraft and the air. Figure 7 shows four different shapes of spikes [11].



(a) (b)

(c) (d)

Figure 7. Four different shapes of spikes. (a) Mesh model of snap spike Vehicle; (b) Mesh model of pan spike Vehicle; (c) Mesh model of blunt spike Vehicle; (d) Mesh model of slender spike Vehicle [11].

In the future, predicting flight conditions before aircraft flight will become increasingly important, so more accurate algorithms and modelling can lead to significant cost savings and increased flight safety. "The shape of the opposed jets in the head of the "blunt" type of vehicle can be optimised to fit a wider range of vehicles.

2.3 Status of Aerodynamic Research

One of the key parts of the hypersonic vehicle, which is fixed to the fuselage, is the wing. Its primary function is to generate lift, which, when combined with the tail, forms good stability and maneuverability. Landing gear, engines, suspended missiles, auxiliary fuel tanks, and other external equipment can be installed on the wings, and ammunition, equipment, and fuel tanks can also be loaded inside the wings. Figure 8 shows the flank of a supersonic aircraft from the Russian "Spiral".

Figure 8. “Spiral” from Russia [6].

A two-dimensional theoretical structural model for the elastic characteristics of supersonic biplanes was developed by Zhou H's group [12]. Computational fluid dynamics/computational structural dynamics (CFD/CSD) and the unsteady Navier-Stokes equations are examined. It is determined that, in a supersonic twin-wing system, the airfoil's stability is poorer than that of an isolated airfoil in supersonic flow, and that this should be taken into consideration during the practical design phase. Research on models is, however, insufficient. Wang et al. [13] mathematically optimized the supersonic airfoil gliders' aerodynamic performance by using the multi-island genetic algorithm (MIGA) with simulated annealing (SA). The findings indicate that the enhanced approach is capable of efficiently resolving the nonlinear, discontinuous, multi-dimensional, and multi-modal optimization design issues associated with gliders. The impact of pressure and resistance data isn't discussed though. The Dodkey S M team examined the supersonic airfoil from the NACA 66 series [14]. An analysis is conducted on the lift and drag coefficients with a constant Angle of attack of Mach 2. Computational fluid dynamics is used to study the pressure, velocity, M, temperature, and Reynolds number distributions on the top and lower surfaces of the airfoil. The outcomes were utilized to ascertain how the lift force produced by NACA 66-206 affected the drag divergence.

The influence of drag and lift distribution on the upper and lower surfaces of the airfoil of a specific aircraft is studied by using a hydrodynamic model to optimize the shape of the airfoil. Its most important role is to produce lift, and together with the tail to form good stability and maneuverability. In addition, ammunition, equipment, and fuel tanks can be loaded inside the wings, and landing gear, engines, suspended missiles, auxiliary fuel tanks, and other external equipment can be mounted on the wings.

2.4 Tailplane Status of Pneumatic Research

Most of the civil fixed-wing aircraft in service include wings, fuselage, tail, landing gear, and power plant, which tail in the aircraft flight process can provide flight stability, control the aircraft around the vertical axis, and pitch steering to improve the manoeuvrability and flexibility, and to a certain extent to improve such as the fuel efficiency of the aircraft and so on many aspects of the benefits, so the tail in the design of civil aircraft is particularly important. Figure 9 shows the A320-232 aircraft tail.

Figure 9. A320-232 aircraft (Photo/Picture credit: Original).

To explore structural design with more optimised performance, domestic and international research institutes have paid much attention to the design of tail fins with different structures. They have explored the aerodynamic characteristics of the aircraft tail using CFD technology, which allows higher resolution capture of the flow field structure in the complex state and more optimised computational time and accuracy compared to the traditional analysis methods [15]. In addition to the effects of the mechanism, the different layouts of the tail fins are also affected. It is found that different tail layouts, such as horizontal, vertical, and tilted wings, have different impacts on the flow field characteristics, aircraft manoeuvrability, and stability, especially on the overall manoeuvrability and vertical manoeuvrability, and a quantitative comparison of different tail layouts with the fuselage has been made to investigate the principle of disturbed flow [16]. The jitter response is a key concern of the industry in designing safety performance, and the characteristics of the jitter response can be simulated and investigated by the coupled hydrodynamic and structural mechanics method, and the jitter response characteristics, such as structural displacement and acceleration, can be effectively predicted [17]. The coupled hydrodynamics and structural mechanics method can be used to simulate the characteristics of jitter response and effectively predict the jitter response characteristics such as displacement and acceleration of structures.

In conclusion, tail aerodynamic shape design is one of the key factors in improving the safety and stability of the aircraft, through continuous optimisation of the design and theoretical methods of simulation and simulation, it can effectively improve the quality of aircraft development.

3 Conclusion

Based on the future research direction of relevant hypersonic aircraft, designing aircraft requires the integration of accurate and fast models and algorithms for simulation experiments, to replace some experimental processes. This can save a lot of design costs and improve the iteration speed of the aircraft model. For the body part, the Hick-Hene method can be used to digitize the body of a single component or a single body, and interpolation can be used to make the results accurate, which can effectively reduce the drag on the body. For the bow part of the aircraft, a coupled calculation method that integrates aerodynamic heat, material erosion, and transient temperature field can be used to estimate the heating conditions accurately and quickly during the flight of the bow, so timely modifications can be made. For blunt-shape head aircraft, adding head-opposed jets can effectively reduce the phenomenon of concentrated heating on the nose. For the wing section, the multi-island genetic algorithm and simulated annealing method can be used to numerically simulate and optimize the aerodynamic performance of the aircraft. For the tail wing section, research finds that different tail wing layouts have different effects on flight stability, operability, and other characteristics in the flow field. Meanwhile, vibration response is an issue that cannot be ignored in the design of safety characteristics. Therefore, more accurate and efficient algorithms and numerical models are key to the design of hypersonic aircraft. This study provides accurate and reliable models and methods for the four important parts of hypersonic aircraft, which have significant reference value. Under the conditions of simplifying and idealizing complex models and equations, the results obtained in this study have a certain degree of error. In the future, optimizing models and algorithms have value in reducing experimental costs, shortening aircraft research time, and improving the performance of hypersonic aircraft.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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