The Contribution of Aircraft External Structural Design for Aerodynamic Performance and Flight Efficiency

Bofan Lin[1*]

[1]School of Optical Information and Energy Engineering and
School of Mathematics and Physics, Wuhan Institute of Technology, Wuhan, China

*2110120211@stu.wit.edu.cn

Abstract. Modern aircraft's external structural design achieves substantial enhancements in flight efficiency and stability through aerodynamic optimisation. Research demonstrates that optimisation of bluntness ratio and semi-cone angle parameters achieves aerodynamic drag balance. In wing design, the SD7003 air foil elevates its lift-to-drag ratio by 15% through surface roughness modulation. Delta wings (leading-edge sweep ≥65°) generate vortex acceleration effects (vortex core velocities 4-5 times freestream velocity) but face abrupt lift loss risks due to vortex breakdown. Swept wings delay shockwave formation to increase critical Mach number yet exhibit a 30% reduction in low-speed lift coefficient compared to conventional air foils and buffet-induced fatigue risks. The Blended Wing-Body (BWB) configuration eliminates interference drag, boosting maximum lift-to-drag ratio by 20%, though requiring 3-5% aerodynamic efficiency sacrifice via negative twist angle adjustments. Wingtip devices reduce ERJ145's induced drag by 5-7% through wingtip vortex reconstruction. Numerically, the RANS/LES hybrid model successfully captures unsteady vortex breakdown characteristics, forming a complementary validation framework with wind tunnel experiments. Practical implementation cases reveal that the Airbus A350 achieves a 25% fuel efficiency improvement through integrated wind tunnel testing and 3d-CAD/CFD tools, confirming the critical role of aerodynamic structural optimisation in modern aviation performance.

Keywords: Aircraft Aerodynamics, External Structural Design, Lift-To-Drag Ratio Optimisation, Wing Configuration, Cfd and Wind Tunnel Validation

1 Introduction

Modern aircraft are facing increasingly complex application scenarios, which put higher demands on the design of the aircraft's external structure. Different air foils have performance degradation under specific operating conditions. For example, the delta wing produces a vortex acceleration effect at high angles of attack (the vortex core speed is 4-5 times that of the free stream), but vortex rupture can cause a sudden drop in lift and flight instability. Although the swept wing can increase the critical Mach number, there are problems such as a 30% reduction in the low-speed lift coefficient and structural fatigue caused by buffeting. The interference drag generated at the traditional

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wing-fuselage connection causes the ERJ series aircraft to suffer an induced drag loss of 7%. These problems directly lead to a decrease in fuel efficiency (the lift-to-drag ratio of the BWB layout is 20% lower than that of the traditional design) and threaten flight safety (swept wing buffeting pressure pulsations cause fatigue risks). Through the innovation of appearance, the BWB wing-body fusion layout is adopted to eliminate interference drag, and the maximum lift-to-drag ratio is improved by 20%; the winglets reconstruct the wingtip vortex, and the ERJ145 induced drag is reduced by 5-7%; the blunt nose ratio and semi-cone angle are optimized to achieve a balance between thermal protection and aerodynamic efficiency. By controlling the roughness of the wing surface and regulating and delaying the separation of boundary layer flow, the lift-to-drag ratio of the SD7003 wing is improved by 15%; by building a complementary verification system of RANS/LES hybrid model (to capture the unsteady characteristics of vortex breakup) and wind tunnel experiments, the Airbus A350 shortened the R&D cycle by 40% through rapid iteration of 3D-CAD/CFD. Aerodynamic optimisation directly affects the core performance indicators of the aircraft. Every 1% increase in lift-to-drag ratio can increase the range by 200-300 kilometres. A 25% increase in the A350's fuel efficiency means saving 15 tons of fuel on a single intercontinental flight. The vortex control technology delays the stall angle of attack by 5-8° , significantly improving the safety of the flight envelope. In general, aerodynamic design has undergone three paradigm shifts, from the Wright brothers' curved wing (1903) to the practical application of swept wings (XB-47, 1947), and then to the application of BWB and smart materials.

This paper will review the design of various parts of the aircraft and explore the impact of the aircraft's external structure on aerodynamic performance and flight efficiency.

2 The Influence of Aircraft External Structure Design on Aerodynamic Performance

2.1 Aircraft Nose Shape Optimisation

The different shapes of the leading edge of an aircraft will affect the aerodynamic performance of the aircraft. Taking the spherical blunt cone volume as an example, the wave drag coefficient of the blunt design is 0.12, and the wave drag coefficient of the pointed cone shape is 0.05. The blunt design sacrifices aerodynamic efficiency in exchange for thermal protection capability [1]. In addition, it is necessary to introduce the concepts of blunt nose ratio (ratio of nose curvature to characteristic length) and semi-cone angle (angle between cone generatrix and normal line). According to research by S. Narayanan* and Rakesh Kumar, the smaller the value of the blunt nose ratio and semi-cone angle, the smaller the aerodynamic drag coefficient of the cone [2]. The corresponding structure is selected according to the different attributes of the mission to be performed by the aircraft.

2.2 The Influence of Air Foil Shape Differences on Aircraft Flight Efficiency

This paper mainly starts from the roughness changes of the air foil surface and the different shapes of the wings and explains the impact of the differences in appearance on the aerodynamic performance of the aircraft.

Effect of surface roughness. According to Zhou's research, the effect of surface roughness on the SD 7003 rectangular wing was analysed by introducing small bumps of different sizes at different locations on the wing surface [3]. The results show that surface roughness can improve the lift-to-drag ratio (L/D) and help avoid flow separation. Increasing the surface roughness of the SD7003 wing surface by adding small bumps can improve the drag ratio (L/D) and help avoid flow separation.

Effects of delta wing swept wing, and BWB on aerodynamics. Delta wing: The wing plane presents a triangular layout, and the leading-edge sweep angle is equal to or greater than 65 degrees. At high angles of attack, the two counter-rotating vortices flowing on the slender delta wing have an axial velocity of the vortex core that can reach 4-5 times the free stream velocity, and the low-pressure area generated significantly increases lift. However, after the vortex breaks, the time-averaged lift and pitch moment decrease, and the breakup position is uncertain, which will lead to a sudden change in aerodynamic performance and affect flight stability and control efficiency [4]. In general, the delta wing gives the aircraft the ability to manoeuvre quickly, but it is not easy to maintain its speed.

Take the swept wing with a leading edge sweep angle of 30° as an example [5]. The swept wing delays the generation of shock waves by reducing the normal Mach number, increases the critical Mach number, and thus reduces wave drag under transonic conditions. The swept wing design improves transonic efficiency by delaying the formation of shock waves, but is limited by the flutter phenomenon, that is, the pressure pulsation and separation zone expansion caused by flutter will cause lift fluctuations, increase drag, and may cause fatigue problems, indirectly causing fatigue problems. In addition, the maximum lift coefficient of the swept wing is generally lower than that of the non-swept wing, resulting in limited lift in the low-speed stage, which will cause aircraft using swept wings to require a longer take-off runway. In addition, the drag on the swept wing surface increases rapidly before stalling, which will lead to a decrease in the drag ratio (L/D), affecting the fuel efficiency and flight performance of the aircraft [6].

Blended Wing Body (BWB) is a tailless aircraft design that forms a single continuous lifting surface by completely integrating the wing and the fuselage. Its core features include geometric integration, structural integration, and aerodynamic integration.

Advantages: Reduced Interference Drag: Compared with traditional aircraft wings, the interference drag at the fuselage connection is eliminated in BWB.

Lower Wetted Area-to-Volume Ratio: BWB significantly reduces skin friction drag by integrating the fuselage and the wing. Theoretically, it is predicted that its maximum lift-to-drag ratio can be improved by about 20% compared with the traditional layout [7]. However, BWB has no horizontal tail and needs to maintain balance through aerodynamic shape adjustments (such as negative twist angle), which may sacrifice some aerodynamic efficiency. Therefore, BWB has higher requirements for the aircraft's control system.

Optimization of wing surface aerodynamics through winglets. In the 3D model of the air foil, the intersection of the high-pressure area and the low-pressure area at the wing tip will generate two counter-rotating vortices on both wings, which will affect the stability of the boundary layer of the wing surface and further affect the aerodynamic efficiency of the aircraft. The design of winglets can effectively solve this phenomenon. Through geometric design, the winglets displace vortices outward, reducing their concentration and rotation intensity, thereby reducing energy dissipation. The winglet, as a vertical or inclined wing surface, generates a lateral lift (Lateral Lift) during flight, and its direction forms a certain angle with the flight trajectory, like the effect of a sail. The horizontal component of lift creates a forward pull that partially offsets the induced drag (offsets energy loss) [8].

By accelerating the airflow in the wing tip area, the wingtip improves the spanwise uniformity of lift distribution and reduces the vortex energy loss caused by the lift gradient. After ERJ 145 is equipped with wingtip winglets, the induced drag is reduced by about 5-7%, significantly increasing the range of the aircraft [9].

3 Structural design optimisation method

3.1 Conventional wind tunnel testing

The main methods for studying aeroelastic problems are numerical calculation, wind tunnel test, and flight test. Wind tunnel test has high reliability.

The lift of a rectangular leading-edge wing drops sharply when it stalls. By analysing the turbulence spectrum with a hot-wire anemometer and comparing the lift and drag curves, it is verified that the serrated leading edge can delay flow separation [10]. By delaying flow separation, the stability of the wing boundary layer can be maintained, ultimately improving the lift of the wing and optimising the aerodynamic efficiency of the aircraft's external structure.

However, the study revealed that the model size and flow rate could not be fully increased due to the limitations of wind tunnel power and space conditions, especially in small-sized aeroacoustics wind tunnels [11]. In addition, for compressor drive systems that rely on air tanks for air supply, the continuous drive time is only a few minutes, and the maintenance cost is high.

3.2 Comparison between CFD and wind tunnel experiments

Compared with the huge cost of wind tunnel experiments, modern CFD can complete the Navier-Stokes simulation of three-dimensional wing-body combinations on ordinary computers. For example, the mature commercial software FLUENT can be used to complete the calculation of related cases. Therefore, the construction and tool design of CFD databases support the participation of non-expert users. Through the

LES/RANS hybrid method, CFD can accurately capture the unsteady characteristics of separated flows (such as vortex breakup and shock wave oscillations) and achieve repeatable analysis of flow states by controlling initial conditions [12].

The changes in the above-mentioned related characteristics will affect the lift-to-drag ratio and flight stability of the aircraft and thus affect the overall flight efficiency of the aircraft.

CFD models also have some difficult problems to solve [13]. The RANS model cannot accurately capture unsteady flow characteristics, such as aeroacoustics noise sources. The predictive ability for free shear flows (such as jets and separated flows) is limited, especially in complex geometries or strong physical coupling scenarios. At the same time, when the LES model is faced with high Reynolds number flow problems, the high-resolution requirement of the wall boundary layer leads to extremely high computational costs, thus limiting the use of the model. Considering the advantages and disadvantages of wind tunnels and CFD, the two experimental methods will continue to coexist for a long time, and the investment in scientific research funds will be saved by numerical simulation, plus wind tunnel experimental verification.

4 Practical application of aircraft external structure optimisation

4.1 Shape Optimisation of Modern Commercial Aircraft

Taking the Airbus A350 as an example, the A380 aircraft achieves a balance between performance and complexity through the combination of leading-edge slats and trailing-edge single-slot flaps to meet the take-off and landing performance requirements of the aircraft under the premise of minimum complexity [14].

For the inner and outer wing sections of the wing, the Droop Nose Device (DND) and CGSS are used, respectively. This effectively reduces the local angle delay airflow separation, avoids the pitching problem caused by the outer wing stall, and allows the aircraft to maintain low resistance during the take-off phase [15]. In the process of aircraft design, the tools and methods used are 3D CAD and CFD tools to accelerate design verification, wind tunnel testing, and flight testing combined. Ultimately, the A350 XWB-900 is 25% more fuel efficient than its competitors [16].

5 Conclusion

The external structural design of modern aircraft achieves performance breakthroughs through systematic aerodynamic optimisation. In terms of aerodynamic shape, the blunt nose ratio (0.12 wave drag coefficient) and the half cone angle optimization balance thermal protection and aerodynamic efficiency; through air foil optimization, the SD7003 wing roughness control improves the lift-to-drag ratio by 15%; the vortex core speed of the delta wing (⩾65° sweep angle) is 4-5 times that of the free stream, but faces the risk of lift mutation; the BWB wing-body fusion eliminates interference drag and improves the lift-to-drag ratio by 20%; the wingtip winglet reduces the induced drag of the ERJ145 by 5-7%; the swept wing improves the critical Mach number at the cost of a 30% reduction in the low-speed lift coefficient.

When designing the aircraft shape, the construction of a RANS/LES hybrid model complements the wind tunnel verification system.

The Airbus A350 achieves a 25% improvement in fuel efficiency through a combination of 3D-CAD/CFD tools, and each 1% increase in lift-to-drag ratio increases the range by 200-300 kilometres. The vortex control technology delays the stall angle of attack by 5-8° .

When designing the appearance, we are faced with a performance contradiction balance. The vortex control technology delays the stall angle of attack by 5-8° ; the BWB layout needs to sacrifice 3-5% aerodynamic efficiency to maintain balance; a contradiction between the swept wing transonic advantage and the low-speed lift loss. There are also risks in the reliability of the aircraft: the contradiction between the swept wing transonic advantage and the low-speed lift loss; the swept wing flutter causes structural fatigue (pressure pulsation reaches the dangerous threshold); the small-scale wind tunnel power limits the model verification accuracy. At the same time, the high Reynolds number calculation cost of the LES model is growing exponentially; the continuous driving time of the traditional wind tunnel is only a few minutes.

The current aerodynamic design has entered the fourth generation of intelligent optimisation. In the next ten years, it is expected to break through the traditional theoretical limitations through AI plus supercomputing technology, give birth to a new generation of configurations with a lift-to-drag ratio of more than 30%, and promote the evolution of aircraft to a more efficient and safer dimension.

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