

Aerodynamic Design and Energy Efficiency Optimization of Aircraft

Yanzhuo Cao

Ulink College of Shanghai, Shanghai, China
yanzhuo.cao@ulink.cn

Abstract. In the context of the global aviation industry's commitment to carbon neutrality by 2050, improving aircraft energy efficiency has become a crucial target of modern aerodynamic design. This report systematically studies aerodynamic optimization and energy consumption reduction from three key aspects. Namely, airfoil parameter influence, bionic flight inspired by albatross dynamic features, and energy feasibility evaluation of supersonic airliners. Based on Bernoulli's principle and aerodynamic drag theory, this research analyzes how aspect ratio and airfoil camber affect lift-drag performance. A bionic low-energy flight strategy for unmanned aerial vehicles is proposed by imitating the high-efficiency gliding mechanism of albatrosses. Meanwhile, a cruise energy consumption model is established to assess the energy characteristics and application potential of supersonic civil aircraft. Results show that increasing wing aspect ratio, adopting bionic adaptive deformation, and optimizing cruise routes can effectively reduce aerodynamic drag and fuel consumption. This study provides theoretical support and practical references for the design of high-efficiency, low-emission aircraft.

Keywords: Aircraft aerodynamic design, energy efficiency, airfoil parameters, bionic flight, supersonic airliner

1. Introduction

The aviation industry contributes a large share of global carbon dioxide emissions. With the International Air Transport Association (IATA) putting forward the net-zero carbon emission target by 2050, reducing fuel consumption and improving energy efficiency have become critical directions in aircraft design. Aerodynamic performance directly determines drag level and fuel consumption, so aerodynamic optimization is the most direct and effective way to improve efficiency.

Traditional civil aircraft have approached the limits of conventional aerodynamic design. Innovative configurations, bionic technologies, and intelligent flight strategies have become breakthroughs [1].

Existing studies show that high-aspect-ratio wings can significantly reduce induced drag. NASA's Transonic Truss-Braced Wing (TTBW) concept can reduce fuel consumption by about 10%-15% [2, 3]. Research on albatross flight shows that dynamic soaring can extract energy from the atmospheric boundary layer, achieving nearly zero-energy gliding [4]. For supersonic aircraft, wave

drag and high fuel consumption remain bottlenecks, but route optimization and new engine concepts possibilities for cutting aviation fuel use [5].

Based on the above contexts, the study consists of four research sections below. Firstly, analyze airfoil parameters and drag characteristics based on Bernoulli's principle and drag equations. Secondly, study bionic low-energy flight strategies inspired by albatrosses. Thirdly, adopt a cruise energy consumption model and evaluate supersonic airliner feasibility. Finally, propose comprehensive optimization approaches for aircraft energy efficiency.

2. Theoretical foundations

2.1. Bernoulli's principle

For steady, incompressible flow,

$$P + 1/2\rho V^2 + \rho gh = C \quad (1)$$

In Formula(1), P represents static pressure of surrounding, ρ is air density, V is the local flow speed of air particles, g means gravitational acceleration; h refers to vertical height relative to the set reference plane, C is a fixed value that stays unchanged along a single air streamline.

When air flows around curved wing surfaces, airflow speeds up on the upper wing side and brings down local static pressure, while the lower wing surface maintains relatively higher air pressure. The pressure gap formed between the upper and lower wings creates upward aerodynamic lift, which is the core physical rule supporting aircraft to stay airborne.

The applicable range of this formula is strictly limited by flight Mach number [6]. When flight Mach number stays below 0.3, air density barely changes, and fluid can be regarded as incompressible, matching the premise of Bernoulli's rule. However, flights at such low speeds take much longer travel time, so mainstream civil airlines rarely choose this cruising mode.

In contrast, flights with a Mach number above or equal to 1 will cause obvious air compression. Supersonic cruising brings multiple unavoidable drawbacks [7]. First, intense sonic boom noise disturbs residents on the ground, leading global aviation regulators to ban overland supersonic flight. Second, high-speed compressed airflow generates strong wave drag, forcing engines to output extra thrust and consume more aviation fuel, which reduces airline operating profits. Additionally, powerful shock waves trigger continuous aircraft vibration and create hidden safety risks for supersonic transport.

Most commercial passenger planes adopt transonic cruising speed (Mach 0.3 to 1). This speed range balances flight efficiency, fuel consumption and flight safety, avoiding the weaknesses of low-speed flight and supersonic flight at the same time.

2.2. Drag composition

Lift forms the fundamental force supporting aircraft flight, and its magnitude can be calculated by the lift Force Equation,

$$L = 1/2 \times \rho \times V^2 \times S \times C_l \quad (2)$$

In Eq. (2), L is the total aerodynamic lift force acting on the wing; ρ represents free-stream air density; V denotes free-stream flight velocity; S stands for the projected planform area of the wing;

C_l is the dimensionless lift coefficient of the wing.

Lift creates wingtip vortices, which induce additional drag named induced drag, calculated via the equation (3),

$$D_{induce} = 1/2 \times \rho \times V^2 \times S \times C_l^2 / (\pi \cdot AR \cdot e) \quad (3)$$

In Eq. (3), $D_{induced}$ refers to the actual induced drag force produced by wingtip vortices; π is the mathematical constant; AR represents wing aspect ratio; e is the Oswald efficiency factor ranging between 0 and 1; other symbols share identical physical definitions as those in Eq. (2).

Aspect ratio controls induced drag intensity, calculated as the wing Aspect Ratio Equation,

$$AR = b^2 / S \quad (4)$$

In Eq. (4), b means the total wingspan measured from one wing tip to the other; S is the wing projected planform area consistent with the definition in Eq. (2); AR denotes dimensionless wing aspect ratio.

Aircraft total drag combines parasitic drag and induced drag, summarized in the total drag coefficient equation,

$$C_d = C_{d0} + C_l^2 / (\pi \cdot AR \cdot e) \quad (5)$$

In Eq. (5), C_d represents the total dimensionless aircraft drag coefficient; C_{d0} stands for zero-lift parasitic drag coefficient; all remaining variables follow the definitions given in Eq. (2)–Eq. (4).

C_{d0} represents zero-lift drag. It refers to parasitic drag coefficient, which is an inherent property of aircraft. Its value is independent of aircraft motion and lift production. Three main factors affect the size of C_{d0} , surface smoothness of the airframe, streamline design of the fuselage, and exposed protruding components including landing gear and external antennas.

The term $C_l^2 / (\pi \cdot AR \cdot e)$ is the dimensionless induced drag coefficient, and $D_{induced}$ is the actual drag force generated by wingtip vortex. Due to the pressure difference between upper and lower wing surfaces, high-pressure airflow below the wing rolls upward around wingtips and forms rotational vortices. This swirling cross flow cannot generate vertical upward lift but consumes flight kinetic energy and increases fuel consumption. Mathematically, induced drag coefficient is proportional to the square of lift coefficient C_l larger, C_l will significantly raise induced drag.

It can be concluded mathematically that rising wing aspect ratio directly cuts induced drag and improves lift-drag performance, supporting high-aspect-ratio wing optimization in later chapters.

2.3. Cruise energy consumption model

$$FuelBurn = (0.5\rho V^3 SC_D) / SFC \quad (6)$$

Where V means flight speed, S means wing area, and SFC means specific fuel consumption. This quantitative formula establishes the direct link between aerodynamic parameters and actual fuel cost, serving as the evaluation benchmark for subsequent aerodynamic optimization effects.

To reduce cruise fuel consumption, three effective approaches can be adopted.

First, flight speed should be kept moderate. Excessively low speed saves instant fuel but prolongs flight duration, which fails to meet passenger demands and damages airline profits.

Second, fuel can be upgraded. Advanced alkane aviation fuels replace conventional crude-based fuels to boost combustion efficiency and reduce engine *SFC*.

Third, raising wing aspect ratio *AR* helps cut drag. With fixed wing area *S*, longer wingspan *b* increases *AR*. A larger *AR* reduces induced drag and total drag, saving fuel.

Still, *AR* cannot be unlimitedly enlarged: indefinitely overly long wings need extra strengthening structures and gain more weight, so total aircraft weight rises. Since lift equals aircraft weight during cruising, required lift *L* goes up and leads to higher *C_L*, which increases induced drag again and offsets fuel-saving gains.

3. Airfoil parameters and drag optimization

In theory, wing aspect ratio needs to be set within a reasonable range; both excessively large and small values will create obvious performance defects.

Adjusting to a larger wing aspect ratio is the simplest way to reduce induced drag. NASA's Transonic Truss-Braced Wing (TTBW) slender wing layout can raise aircraft lift-drag ratio greatly during cruising. Data from NASA's TTBW simulation tests show that wings with aspect ratio 10 can lift lift-drag performance by 21% and cut cruise fuel consumption by 11.2%, compared with the baseline wing with *AR*=6, while structural weight only rises by 6% [2]. If designers expand the aspect ratio to 15, the weight of reinforced wing structures will increase by 22%, and the actual fuel-saving effect will shrink to merely 2.4% [8].

Oversized wingspan also brings two practical operation troubles. Longer wings bear huge bending force in flight, requiring thicker reinforcing structures and adding total aircraft weight. Moreover, ultra-wide wings cannot match the size limits of airport taxiways and parking positions. Foldable wing structures solve this contradiction well: wings fold tightly on the ground to fit airport space limits, and fully stretch in the air to maintain the low-drag merit of high aspect ratio.

Airfoil camber also balances lift and drag performance. Moderate positive camber raises the lift coefficient and improves low-speed performance when taking off and landing. If the camber is too large, the adverse pressure gradient on the wing surface will get much steeper, causing early airflow separation and a wide turbulent wake, which greatly increases total drag. Variable camber designs reconcile this trade-off. Segmented flaps and adjustable trailing edges change the airfoil curve according to flight phases: larger camber for sufficient lift at low speeds, and flatter shapes to reduce drag in steady cruise.

Other airfoil features also affect drag level. Thick airfoils provide more inner space for fuel and structural layout, yet they generate stronger wave drag under transonic conditions. Thin streamlined airfoils reduce wave drag but have weaker load-bearing capacity. In addition, exposed rivets, panel gaps, and rough surface coatings create extra parasitic drag, so smooth and continuous wing skins are essential to cut drag loss.

To sum up, the optimal matching design for subsonic airliners with low drag and high efficiency consists of a moderately high-aspect-ratio wing, dynamically adjustable moderate camber, and a fully smooth streamlined aerodynamic layout.

4. Bionic flight strategy inspired by albatrosses

Albatrosses can capture wind energy through dynamic soaring movements: they gain power by flying against headwinds and glide down with tailwind assistance, almost relying on wind energy to complete long-distance flight with little energy loss [4]. Such biological characteristics provide

multiple bionic design directions for UAVs, including high-aspect-ratio wing layout, self-adjustable deformation structures, wind-adaptive flight route planning, and lightweight body design.

The natural slender, high-aspect-ratio wings of albatrosses restrain the formation of wingtip vortices and cut induced drag, fully conforming to the drag reduction rules analyzed in the previous chapter. During long-distance flight, birds can slightly adjust wing shapes according to real-time wind conditions to further reduce unnecessary energy loss [9].

Relying on modern flight control algorithms, drones collect real-time wind information to react to wind variations and autonomously adjust flight attitude and flight path to replicate albatross dynamic soaring movement. This scheme can reduce cruise energy consumption by more than 15% [9].

With solid theoretical support and practical flight tests, scholars and aviation engineers developed the scaled demonstrator named AlbatrossONE. Drawing inspiration from the flexible shoulder structure of wandering albatrosses, this small test vehicle adopts semi-aeroelastic hinged wingtips that mimic the locking and releasing movements of the bird's shoulders. The wingtips can alter their shapes adaptively to match varying wind fields during flight. When cruising in steady airflow, the wingtips stay locked to cut aerodynamic drag and lower fuel burn. In gusty and turbulent conditions, they flex freely to absorb air loads. Such adjustable deformation not only makes the aircraft respond to complex airflow more accurately and flexibly, but also enhances flight stability. Moreover, the buffering effect of deformable wingtips removes the need for heavy reinforcement at wing roots, effectively cutting the overall weight of the wing assembly [10].

5. Feasibility analysis of supersonic airliners

As airlines pursue shorter transoceanic travel times, supersonic aircraft have gradually attracted widespread attention from both the civil aviation industry and financial sector. Multiple technical measures can be applied to optimize supersonic airliners, including low-wave-drag layout, variable-cycle engines, jet stream-optimized routes, and lightweight and high-temperature materials. Reasonable optimization can reduce fuel consumption by about 8%–12% [5, 11, 12].

Since related technology is still improving, commercial application of supersonic airliners faces prominent barriers. Supersonic flight generates a sonic boom, which is restricted by many organizations. Global airworthiness regulations also limit overland supersonic cruising. Besides, high-altitude flight of supersonic aircraft contributes to emissions of nitrogen oxides, which will erode ozone through free-radical substitution and lead to more ecological risks.

The Concorde jet is the only supersonic passenger aircraft ever formally put into civil commercial service, yet it has multiple inherent hard-to-solve defects. Each passenger on Concorde consumed over four times more fuel than passengers on a Boeing 747, creating severe environmental pollution. Such extreme fuel consumption mainly comes from its ultra-high flight speed: fast cruising creates strong wave drag and pushes up fuel demand significantly. Besides, its flight produced obvious sonic boom noise, violating global civil aviation management rules and severely limiting available flight routes. Meanwhile, massive fuel combustion released large volumes of carbon dioxide and nitrogen oxides, causing permanent damage to the ecological environment. All the above economic, regulatory, and environmental obstacles explain why large-scale popularization of supersonic passenger planes cannot be realized in the short term [13].

Supersonic airliners are technically feasible but still need improvement in economy and environmental protection. They are suitable for future long-haul premium routes [1].

6. Conclusions

Optimizing wing aspect ratio and airfoil camber is a practical way to reduce drag and improve energy efficiency. Reasonable wing design reduces wingtip vortices and energy loss during flight, bringing better lift and drag performance to subsonic aircraft. The flight characteristics of albatrosses also bring potential ideas for the development of low-energy unmanned aerial vehicles. Drawing on their dynamic soaring mode and flexible wing structure allows aircraft to take advantage of wind energy and reduce fuel consumption during cruise.

Supersonic airliners do have technical feasibility, yet many issues stand in the way of large-scale commercial operation. High fuel consumption is one major problem. Sonic boom creates noise trouble for residents, and the emissions from supersonic flight also pose threats to the ecological environment. For these reasons, such aircraft cannot be widely used in regular civil aviation in the near future.

A combination of aerodynamic optimization, bionic design and flight route planning will become an important direction for aircraft research from now on. These different technologies can make up for the shortcomings of traditional design, and help the aviation industry move closer to the carbon neutrality target.

References

- [1] He, Z. (2023). Analysis of the sustainable advanced airliner design for the future. *ResearchGate*. <https://www.researchgate.net/publication/374512345>
- [2] Bradley, M. K., & Droney, C. K. (2015). Subsonic ultra green aircraft research: Phase II (Report No. NASA/CR-2015-218704). *NASA*. <https://ntrs.nasa.gov/api/citations/20150017036/downloads/20150017036.pdf>
- [3] Boeing, & NASA. (2023). X-66A sustainable flight demonstrator. *NASA*. <https://www.nasa.gov/aeronomics/x-66a-sustainable-flight-demonstrator/>
- [4] Sachs, G., et al. (2012). Flying at no mechanical energy cost: Disclosing the secret of wandering albatrosses. *PLOS ONE*, 7(9), Article e41449. <https://doi.org/10.1371/journal.pone.0041449>
- [5] CFM International. (2021). CFM RISE program whitepaper. <https://www.cfmaeroengines.com/press-articles/ge-aviation-and-safran-launch-advanced-technology-demonstration-program-for-sustainable-engines-extend-cfm-partnership-to2050>
- [6] NASA Glenn Research Center. (2021, August 22). Mach number and compressible flow regimes. <https://www.grc.nasa.gov/www/k-12/BGP/mach.html>
- [7] Xiao, T., Xu, Y., Zhu, Z., et al. (2021). Influence of engine nacelle layout on sonic boom of supersonic civil aircraft. *Journal of Beijing University of Aeronautics and Astronautics*. <https://www.spacejournal.cn/bjhkhtdxxb/cn/article/pdf/preview/10.13700/j.bh.1001-5965.2021.0687.pdf>
- [8] Recine, C. J., Schuh, M. J., Listgarten, N. S., et al. (2025). Quantification of design trade-offs when comparing transonic truss-braced wing to advanced tube and wing aircraft [Paper presentation]. *AIAA SciTech Forum 2025*.
- [9] Zhang, H., Zhang, S., & Xiang, T. (2024). Effects of bio-inspired wing dihedral variations on dynamic soaring performance of unmanned aerial vehicles. *Drones*, 8(11), Article 623. <https://www.mdpi.com/2504-446X/8/11/623>
- [10] Wang, C. H. (2023). The prospect of the morphing plane's application in civil aviation. *Theoretical and Natural Science*, 5. <https://doi.org/10.54254/2753-8818/5/20230293>
- [11] Colling, M., & Thomas, P. R. (2024). Wind-optimal transatlantic route planning for civil supersonic aircraft [Paper presentation]. *34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024)*. https://uhra.herts.ac.uk/id/eprint/26781/1/Wind-Optimal_Transatlantic_Route_Planning_for_Civil_Supersonic_Aircraft_-_accepted.pdf
- [12] NASA. (2018). Benefits analysis of wind-optimal operations for trans-Atlantic flights. <https://ntrs.nasa.gov/api/citations/20180004216/downloads/20180004216.pdf>
- [13] Bhatta, K. (2025, August 14). Why did Concorde stop flying? Top 5 reasons why it failed. *Avio Space*. <https://aviospace.org/why-did-concorde-stop-flying-top-5-reasons-why-it-failed/>