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Aerodynamic Features of Subsonic Aircraft Wing Design

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Abstract. This article focuses on the use of physical theory in designing aircraft wing as well as how to improve the aircraft wing's performance. Starting with three key constraints—fuel efficiency optimization, FAA/EASA certification requirements, and airport facility limitations. The study systematically analyses the relationship between aerodynamic principles and the shape of the wings in design. Fuel efficiency, a vital factor influencing operational costs and environmental sustainability, can be improved primarily via optimizing the aspect ratio (AR) and aerodynamic layout. This could effectively reduce the drag force, for example, the Airbus A350's AR is 11.3 whose drag force is decreased by 30%. Additionally, FAA and EASA have strict standard for civil aircraft. Also, the limits of the airports and the wingspan constraints (ICAO Code A-E standards) promote the innovations like folding wingtips (Boeing 777X) and short-runway adaptability (high-lift slat/flap systems.). Furthermore, Boeing 737 MAX has a winglet to increase fuel efficiency by reducing induced drag. Nevertheless, scientists and engineers have made considerable efforts to improve aircraft's aerodynamic performance.

Keywords: Subsonic aircraft, wing design, aerodynamic

1. Introduction

As the principal aerodynamic element of subsonic passenger aircraft, wing directly decides the airworthiness, safety and availability of the whole aircraft. With the rapid development of the global civil aviation industry, the sector is confronting dual pressures: rising fuel costs and stringent environmental regulations (e.g., carbon emission reduction targets). Hence the new aircraft must be more efficiency, more powerful. Owing to this background, the requirement of efficiency and cruise speed of the next-generation aircraft becomes really important. Correspondingly, improvement of wing performance is making great concern. A number of innovations were developed after in a decade, such as the folding wingtip technology developed by Boeing using for their new wide-body airliner Boeing 777X and the widespread application of supercritical airfoil and the carbon fiber reinforced polymer (CFRP). All these advances have proved the great possibility of the development of wings to be improve the aircraft's comprehensive capabilities, we will discuss the basic physical concepts and optimization directions of wing design.

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2. Factors and principle

2.1. Fuel efficiency optimization

Since fuel efficiency determines the operating economy and environmental friendliness of passenger aircraft, the wing as the key component of aircraft aerodynamics decreases the consumption of fuel to achieve the maximal lift-drag ratio, which includes emphasis on the range of wing-span/wing area and the layouts of wing aerodynamics.

2.1.1. Aerodynamic optimization of wingspan and wing area

The aspect ratio ($AR = b^2/S$), the ratio of the wingspan (b) to the area of the wing (S), is an important factor affecting induced drag. The simple concept of aerodynamics tells that the lift is only the pressure difference between the upper and lower parts of the wing, which is calculated by the following formula:

$$L = (1/2)\rho V^2 SCL \tag{1}$$

Physical interpretation: ρ (air density, standard value at sea level is 1.225 kg/m3), V (flight speed), S (wing reference area), CL (lift coefficient, depends on angle of attack) provide the lift. For a given take off weight, S and CL have to be tuned so that the lift is sufficient. The induced drag is the cost of lift, produced by the wingtip downwash. Its coefficient is given by:

$$CDi = CL2/(\pi e AR) \tag{2}$$

Physical interpretation: A bigger Oswald efficiency factor (e, aerodynamic property of the wing, e ~ 0.7–0.9) and larger AR lead to a smaller induced drag coefficient. Hence, increasing AR can make the induced drag small, but it must be balanced with the structural weight (a longer wingspan is detrimental to the wing bending stress).

Engineering examples show that Airbus A350 uses a high-aspect ratio design (AR = 11.3) combined with a sharklet winglet, which decreases the induced drag by 30%, and improves the fuel economy by 25% compared with the previous generation aircraft [1]. Such "high aspect ratio + wingtip device" solution has become the mainstream idea of today's generation of subsonic passenger aircraft [2].

Figure 1 shows the curve of induced drag coefficient to lift coefficient for various AR (wind tunnel test results). The curve indicates that as AR increases from 8 to 12, induced drag coefficient CDi decreases from 0.012 to 0.007 when lift coefficient CL is the same (for example, 0.5), also verifying the reduction of drag caused by a higher aspect ratio. The horizontal axis is lift coefficient CL (0–1.2) and the vertical axis is induced drag coefficient CDi (0–0.015), and the curves are labelled with three sets of parameter values: AR=8, 10, and 12 [3].

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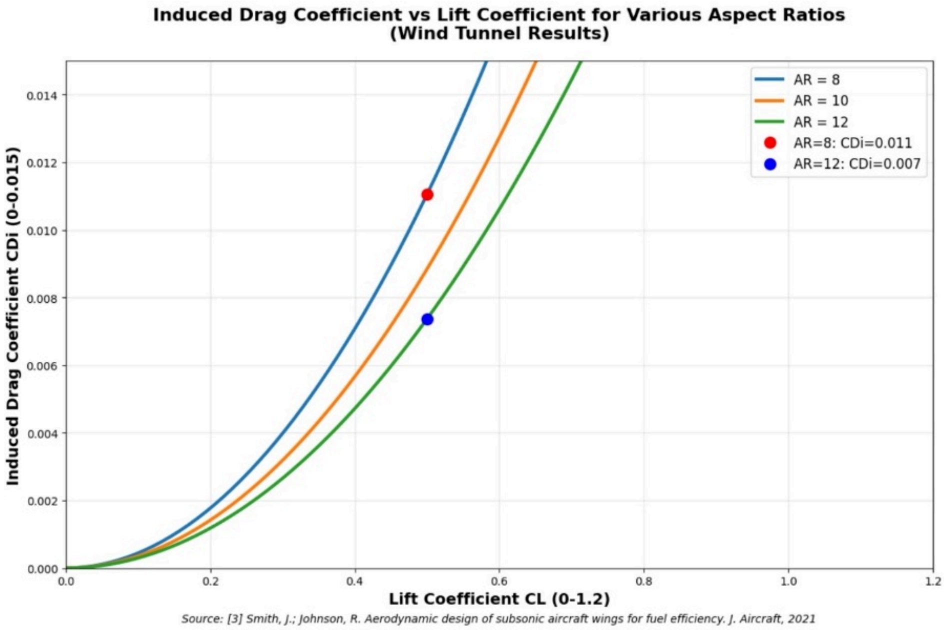

Figure 1. Induced drag coefficient vs lift coefficient for various aspect ratios [3]

2.1.2. Design for drag reduction of aerodynamic layout

Optimization of the aerodynamic layout of subsonic passenger aircraft considers the sweep angle and wingtip devices, the main aim is to minimize wave drag and induced drag, and to improve lift-to-drag ratio (L/D).

Where Λ is a sweep angle, which is defined as the angle between the aircraft wing leading edge and the body of aircraft. Its main function is to postpone the appearance of the transonic shock wave. As the aircraft flight speed approaches the critical Mach number (Macrit), the flow velocity at the upper surface of the wing is greater than the sonic velocity, and a shock wave is generated and wave drag appears.

Wave drag coefficient and Mach number relationship is: $CDw \approx (Ma - Macrit)^2 / \sqrt{(1 - Ma^2)}$ Physical interpretation: closer Mach number Ma (flight Mach number) is to Macrit, the increase of wave drag becomes slower; increase sweep angle can raise Macrit (e.g. Λ=30°, Macrit is 15%~20% higher than straight wing) and result in notable reduction of wave drag in the subsonic range (Ma = 0.7, 0.85) [4].

Winglets reduce induced drag without significantly increasing wing structural weight by deflecting wingtip airflow and weakening the strength of wingtip vortices. Lift-to-drag ratio (L/D = CL/CD) is an important criterion for evaluating flight efficiency. Optimizing sweep angle and wingtip shapes can obtain an L/D ratio of 18–22 for subsonic passenger aircraft (for example, the L/D ratio for Boeing 787 is 20) [5], an improvement on existing models of around 10–15%.

Figure 2 shows two parts: the left part gives the effect of the sweep angle on the wave drag coefficient (horizontal axis: Mach number Ma=0.6 to 0.9; vertical axis: wave drag coefficient CDw=0 to 0.02), from which it can be seen that the CDw of Λ=35° is 28% smaller than that of Λ=25°; the right part is a schematic diagram for control of airflow by winglets, labeling the direction of vortex deflection, change in pressure distribution, and so on [6].

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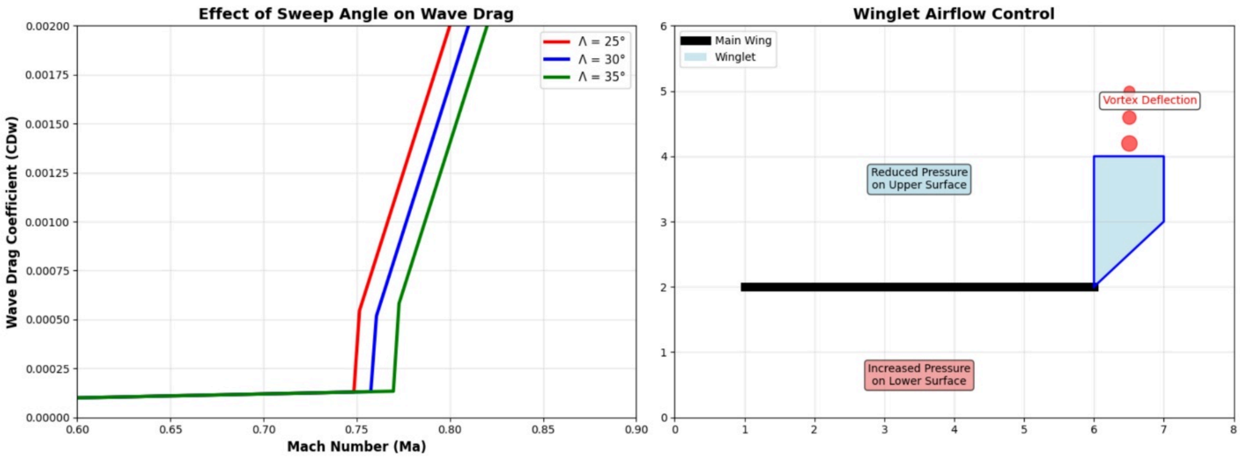

Figure 2. Sweep angle's wave drag effect & winglet airflow control [6]

2.2. FAA and EASA certification requirements

While certification standards of the FAA (Federal Aviation Administration) and EASA (European Union Aviation Safety Agency) are mandatory requirements for the wing design, which consider aerodynamic safety and stability of performance mainly in terms of 14 CFR Part 25 (FAA) and CS 25 (EASA) standards [5].

2.2.1. Aerodynamic characteristics certification indicators

Stall characteristics: the maximum lift coefficient (CL,max) should be greater than the required critical stall lift coefficient (CL,stall) by over 30%, that is, CL,max ≥ 1.3×CL,stall, providing ample lift margin in the low speed flight (e.g. take-off and landing) to avoid stall [7].

Stability requirement: for the Mach number 0.3~0.85, the rate of variation of CM of the wing is less than or equal to 0.02/deg to meet the attitude stability flight.

Efficiency of high-lift devices: When the flaps and slats are deployed, CL should increase by more than 60% to assure a short runway takeoff and landing ability (such as, the FAA always gives the runway takeoff requirement to be ≤ 2000 m and the landing runway requirement to be ≤ 1800 m, under standard sea level conditions) [8].

2.2.2. Certification test process

For certification, two verifications, wind tunnel tests and flight trials, are needed: the wind tunnel test takes the 1:8—1:10 models, which is to simulate the aerodynamic characteristics of the aircraft at different Mach number and angle of attack; the flight trial requires at least 500 take-off and landing trials, and cruising trials to record the actual flight data, such as lift-drag test and stall test, etc. [9].

For example, the wing design of the Boeing 787 and Airbus A350 underwent rigorous testing for certification purposes [6].

Table 1 is a comparison chart for the main certification items of the wings of subsonic passenger aircraft for FAA and EASA. Columns include"Certification Item","FAA requirement","EASA requirement", and four main indexes in total, including stall margin, lift to drag coefficient, the efficiency of high-lift device and stability [5], etc.

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Table 1. FAA vs EASA certification requirements for subsonic passenger aircraft wings [5]

Certification Item	FAA Requirement	EASA Requirement
Stall Margin	CL,max≥1.3xCL,stall	CL,max≥1.3xCL,stall
Stability(Pitching Moment Variation)	dCm/dα≤0.02/deg(Ma=0.3-0.85)	dCm/dα≤0.02/deg(Ma=0.3-0.85)
High-lift Device Efficiency	ΔCL≥60% with flaps/slats deployed	ΔCL≥60% with flaps/slats deployed
Lift-to-Drag Ratio (L/D)	Verified via flight tests	Verified per CS-25 Standards

2.3. Complying with airport takeoff and landing requirements

Wing design has to adapt to the limitations of prevailing airports all over the world, and the limiting factors comprise wingspan, parking space and runway length.

2.3.1. Wingspan and airport compatibility

As illustrated in Figure 4, ICAO (International Civil Aviation Organization) classifies airports into five grades (Code A-E). Code E airports can accommodate aircraft with maximum wingspan of 65 meters [10]. To serve different airports, modern passenger aircraft are designed into two schemes: (1) wingspan optimized: e.g., Airbus A320neo (wingspan 35.8 m), fit for Code C/D airports; (2) Folding wingtip technology: e.g., Boeing 777X ensuring aerodynamic efficiency and parking availability [11].

2.3.2. Design optimization for short-runway take-off and landing aerodynamics

At short-runway airports (runway length ≤ 1800 meters), the wings must induce more lift at low speed by using high-lift devices. The lift formula still applies:

$$L = (1/2)\rho V^2 SCL \tag{3}$$

Design focus: By means of leading edge slats (to increase effective wing camber) and trailing edge flaps (to increase wing area), CL is increased to 1.8–2.2 for take-off and landing (CL ≈ 0.5–0.8 for cruise) so as to produce enough lift with low airspeeds (V = 250–300 km/h) [10]. For example, the winglets on the Airbus A320neo can be folded to adapt to narrow hangars [11].

Figure 3 is a schematic showing the folding wingtips parked or flying states, right hand side is the relationship between wingspan and airport compatibility [12]. 2. Study to optimize aerodynamic drag of passenger aircraft wings.

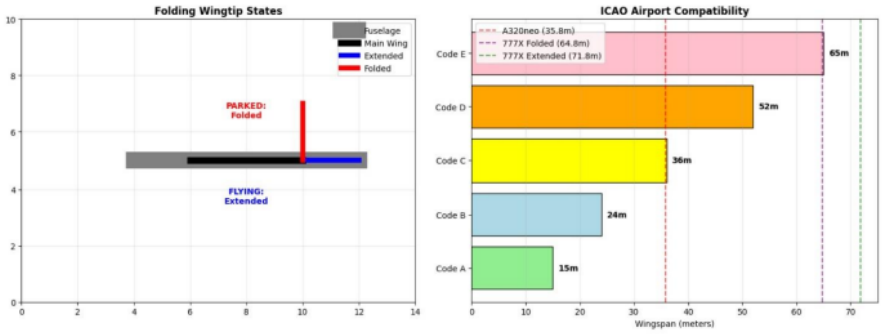

Figure 3. Folding wingtips and airport compatibility [12]

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As aerodynamic drag is a primary factor for passenger aircraft fuel efficiency, and skin friction drag, induced drag, and wave drag are the main components of the total drag (50%, 30% and 20% in the subsonic cruise conditions, respectively), in the following, the optimization methodologies for each kind of drag are discussed:

3. Ways to improve

3.1. Skin friction drag optimization

Skin friction drag is the shear effect due to air viscosity on the wing surface and accounts for more than half of the subsonic cruise drag. Its coefficient formula is derived from Prandtl's boundary layer theory: CDf = 0.074/Re^0.2, where Re (Reynolds number) = ρVL/μ (L is wing chord length; μ is air dynamic viscosity); a larger Re value means a smaller CDf; higher surface roughness leads to a higher CDf [13].

Optimization measures mainly include: (i) Material selection. Use carbon fiber composite materials (such as Airbus A350 wings) which is smooth, so that the skin friction drag of wings is reduced by 5%~10% compared with aluminium alloys [10].

Chart description: Figure 4 is the curve of skin friction drag coefficient of smooth surface with respect to surface roughness (Re=5×10^6, subsonic cruise), horizontal axis: surface roughness (μm, 0—20), vertical axis: CDf (0—0.005), verifying the drag reduction effect of smooth surface [13].

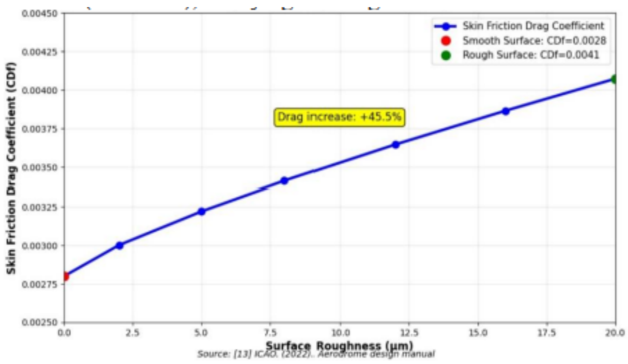

Figure 4. Effect of surface roughness on skin friction drag [13]

3.2. Induced drag optimization

Induced drag is the extra drag that is a side effect of lift, due to wing tip vortices. The core of induced drag optimization is to reduce the vortex intensity, and the typical approaches are:

3.2.1. Aspect ratio optimization

As in Section 1.1.1, large values of AR reduce CDi, but one needs to consider the structural weight. The AR of present subsonic passenger aircraft is typically 8–12, thus reducing induced drag by 20–25% with respect to more conventional craft [1].

3.2.2. Innovation in wingtip devices

Other than winglets, new wingtip devices (such as sharklets, raked wingtips) also help increase the efficiency of drag-reduction devices. For example, the Boeing 737 MAX has a winglet to increase

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fuel efficiency by reducing induced drag [12].

Figure 5 presents changes in induced drag with wingspan and winglet design. It shows that raked wingtips have the lowest CDi [2].

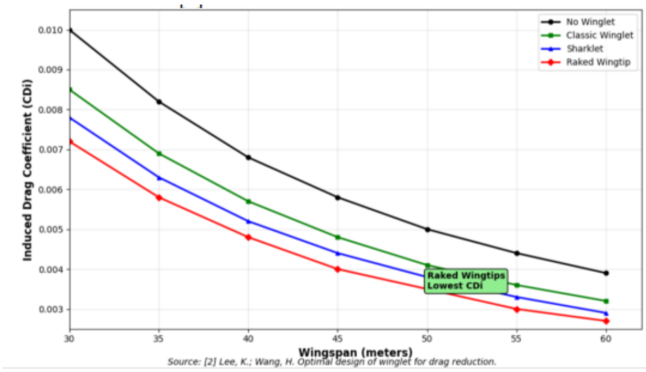

Figure 5. Include drag vs wingspan and winglet design [2]

3.3. Wave drag optimization

Wave drag in the subsonic passenger aircraft happens primarily in transonic range (Ma=0.7~0.85). The primary issue of optimization is to delay shock formation, the prominent technology is supersonic wing design.

The supercritical airfoil has a “flat trailing edge + curved leading edge” shape, which weakens the shock intensity and decreases the wave drag by 30–40% [9]. Engineering examples include the Airbus A350 which has a supercritical airfoil that increases the critical Mach number from 0.75 to 0.82 and the reduction of wave drag is 15% [3].

Chart Description: Figure 6 compares wave drag of a traditional and a supercritical airfoil in the transonic region. Supercritical airfoils have lower CDw at Ma > 0.75, generally [4].

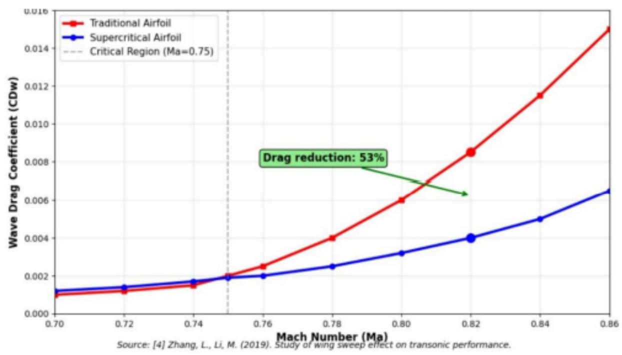

Figure 6. Wave drag comparison: traditional vs supercritical airfoil [4]

4. Conclusion

In conclusion, it is found that there are three key factors in designing aircraft wings which include fuel efficiency optimization, FAA/EASA certification requirements, and airport facility limitations. To improve the performance of wings, people have made a lot of attempts, for example, use a high-aspect ratio design and innovated such as folding wings (Boeing 777X), and carbon fiber composite wings (Airbus A350). Through the verification of scientific models and practice, these designs do effectively improve the performance of the aircraft wings.

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