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Principles and examples of drag reduction in civil airliners

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Abstract. Civil aviation has grown rapidly over the past hundred years as demand from air travellers has increased. Since the mid to late 20th century, there have been recurring global energy crises due to political and economic upheavals. In this international context, airlines have tended to operate less draggy, more fuel efficient aircraft in order to maximise profits through fuel cost savings . To this end, aircraft manufacturers have historically tried a variety of methods to address the issue of drag reduction.This paper highlights the importance of three drag reduction methods utilized on modern subsonic airliners by introducing their basic principle and evaluating their effectiveness based on previous research and typical experiments. This paper summarizes and analyzes different approaches to reduce drag in civil aviation. It first investigates the principle behind frictional, induced, and profile drag in theoretical aspects. It then discusses in detail the biomimicry microstructure based on shark skin and its uniqueness on aircraft fuselage's surface to reduce frictional drag, the split scimitar winglet and its ideal performance to reduce induced drag when compared with other wingtip devices with different cant angles. The newly introduced adaptive lifting surface changes the wing's geometric configuration momentarily, and its ability to reduce profile drag at different stages of flight. This paper also comprehensively compares both the benefits and potential compromises of these drag reduction methods.

Keywords: winglet, frictional drag, adaptive lifting surface, drag reduction.

1. Introduction

Over the past century, civil aviation developed rapidly with the increasing demand from air travelers. Since the early 1970s, the global energy crisis repeatedly occurred due to political and economic unrest. In this international context, airline companies tend to operate aircraft with lower drag and higher fuel efficiency in order to maximize profits by saving fuel costs [1]. To this end, aircraft manufacturers historically attempted multiple approaches to the topic of drag reduction.

In the early days of aviation, planes usually had relatively rough and irregular surfaces due to immature technology. Around 1930, researchers noticed that the surface tolerance, which influences the magnitude of smoothness of the fuselage skin, will reduce the aircraft's drag-to-lift ratio by creating viscous drag [2]. In the mid-1970s, NASA launched a research program to reduce the viscous drag, which accounted for approximately 50% of the drag for subsonic planes in the cursing phase [3]. Micro-geometrically, researchers altered the wing with suction holes to better control laminar flow, resulting in a 20% reduction in the total drag. In addition, with technological advancement, electronic and micro laser beams were available to drill suction holes in the 1990s, helping the plane to control laminar flow [4]. In other studies, researchers focused on minimizing surface imperfections, which impact the local adverse pressure gradient, by optimizing the shape of rivets and the material of fuselage skin [5].

Other common approaches reduce drag by manipulating the aircraft's wing on a macroscopic view. The most obvious method is to change the aspect ratio of the wing. In 1984, researchers from Texas A&M University investigated the relationship between the aspect ratio and drag force. The result showed that drag will decrease as the aspect ratio decrease [6]. Besides, wingtip devices known as "winglets" are also a major research focus. In 1986, Thomas Moore investigated the effect of winglets on the wing of KC-135 aircraft by alternating the different parameters, such as toe and twist angle, in a computer simulation. The result strengthened researchers' understanding of the shape of an ideal winglet [7].

Over the past five years, continued uncertainties have posed huge global challenges for the civil aviation industry. Unfortunately, besides the frequent fluctuation of oil prices, the pandemic put airlines in a difficult position. According to IATA, the demand for air travel decreased by more than 50% in 2020, causing a net loss of 110 billion USD [8]. Technologies that improve fuel efficiency are needed in this stagnant market to reduce airline operation costs and accelerate the industry's recovery. Moreover, as global warming continues to intensify, IATA aimed for a 50% reduction of net carbon emissions in the industry by 2050, revealing the importance and urgency of increasing fuel efficiency [9]. Based on research, around 85% of drag in today's commercial aircraft comes from skin friction and induced drag, highlighting the importance of further investigation in both fields [10]. Researchers developed several new drag reduction methods in response to the current situation.

Regarding frictional skin drag, researchers are inspired by the biological features of animals. For example, since sharks can swim with high velocity in water, researchers try to apply microscopic structures on shark skin to aircraft surfaces in order to decrease friction drag. After a thorough study, researchers noticed that shark skin consists of numerous dermal denticles, microscale components of a riblet surface. This special surface may keep the vortex to the lowest level, making a 12% drag reduction compared to the smooth surface [11]. Focusing on wingtip designs, researchers propose to add wingtip-mounted propellers to the airplane as an alternative device to traditional winglets. After the takeoff, the propellers will spin, and, by creating a swirl, the high-frequency rotation will act against the wingtip vortex, decreasing both its intensity and the strength of downwash. Moreover, the propeller's advantage (decrease in induced drag) outweighs its potential disadvantage (increase in skin friction drag due to the wing behind the propeller's slipstream) [12].

To achieve the same objective of reducing induced drag, Nikolaos Kehayas works from a different approach. Supported by the lifting line theory, the researcher combined astroid and elliptical shapes of hypocycloid lift distribution to reduce the drag to the largest extent. Ideally, by manipulating the distribution of lift, the wing's center section will generate more lift, and lift at the wingtip will gradually fade away. In this way, the wing vortex will be reduced by 50%, decreasing the drag and increasing the fuel efficiency significantly [13]. However, this proposal is only based on theoretical calculations, which do not consider the material and structural constrain of the wing. This may limit the feasibility of future research.

To further optimize the existing drag reduction methods, Aaron Cusher and Ashok Gopalarathnam discuss the use of adaptive lifting surfaces to reduce inflight air drag, specifically by optimizing multiple surface configurations using design variables like incidence, twist, and flap angles to minimize induced drag while also considering profile drag. The skin-friction drag contributed the to profile drag in subsonic airliners, and designers typically decrease air pressure in the direction of airflow to maintain laminar flow over wing surfaces and reduce drag. The use of adaptive lifting surfaces like trailing-edge flaps can extend the low-drag range [14].

This paper highlights the importance of three drag reduction methods utilized on modern subsonic airliners by introducing their basic principle and evaluating their effectiveness based on previous research and typical experiments. This paper summarizes and analyzes different approaches to reduce drag in civil aviation. It first investigates the principle behind frictional, induced, and profile drag in theoretical aspects. It then discusses the biomimicry microstructure based on shark skin and its uniqueness on aircraft fuselage's surface to reduce frictional drag, the split scimitar winglet and its ideal performance to decrease induced drag when compared with other winglets with different cant angles. The newly introduced adaptive lifting surface changes the wing's geometric configuration momentarily, and its ability to reduce profile drag at different stages of flight. This paper also comprehensively compares both the benefits and potential compromises of these drag reduction methods.

The study of different drag reduction methods of civil aircraft may benefit the future of the civil aviation industry. In particular, it can improve the efficiency of the whole industry by mainly increasing the fuel efficiency to achieve the goal of annual 1. 5% fuel efficiency improvement set by IATA, dedicated to reducing carbon emission and fuel cost [15]. Moreover, it indirectly increases the maximum operational range [16] and minimizes the potential danger from wake turbulence [17].

2. Theoretical analysis of drag force reduction

2.1. The principle of reducing the frictional drag on aircraft body surface

There are many forms of fluid resistance. In the research of aircraft, there are two main resistances worth discussing. One is pressure resistance, and the other is friction resistance. When it comes to aircraft, a streamlined shape can be used to lower pressure drag, but reducing frictional resistance is much more complicated. When the flow state of the fluid changes, or the flow field changes, the fluid that was originally in a laminar flow state will produce small unstable fluctuations in a specific area, and then turn into a turbulent flow. The unstable turbulent flow interacts with the surrounding fluid in the moving flow field, thus forming many vortices. During migration, the collision of nearby vortices and the contact of vortices with objects causes a degree of momentum exchange and kinetic energy loss, which is an important reason for the high frictional drag of fast-flying aircraft. Figure 1 illustrates the transition of the fluid to different states in different situations.

Nature has many biological evolutionary achievements that can be used for human reference. Sharks can swim fast thanks to the groove-like structure of their skin surface arranged in the direction of flow. And it has been revealed that this microstructure decreases the surface frictional drag force in turbulent flows. With the rapid development of bionics in recent years, many research teams also hope to apply this technology on shark skin in aircraft.

According to studies, shark skin has an extremely rough surface and is not smooth. Under a microscope, this rough surface reveals a characteristic grooved microstructure, a feature that prevents the vortices generated on its surface from touching the shark's skin. Figure 2 shows the epidermal structure of a shark observed by electron scanning microscopy.

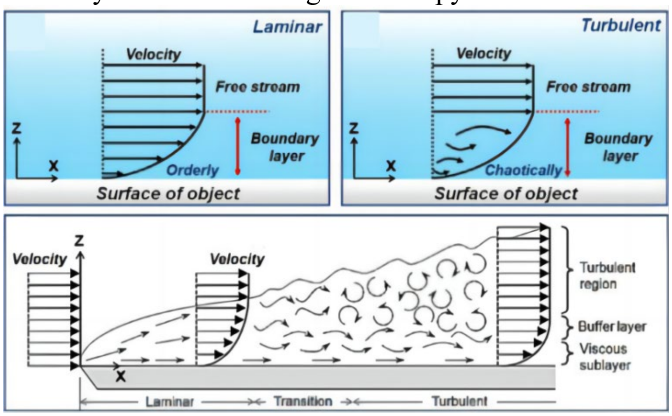

Figure 1. Forms of fluid flow.

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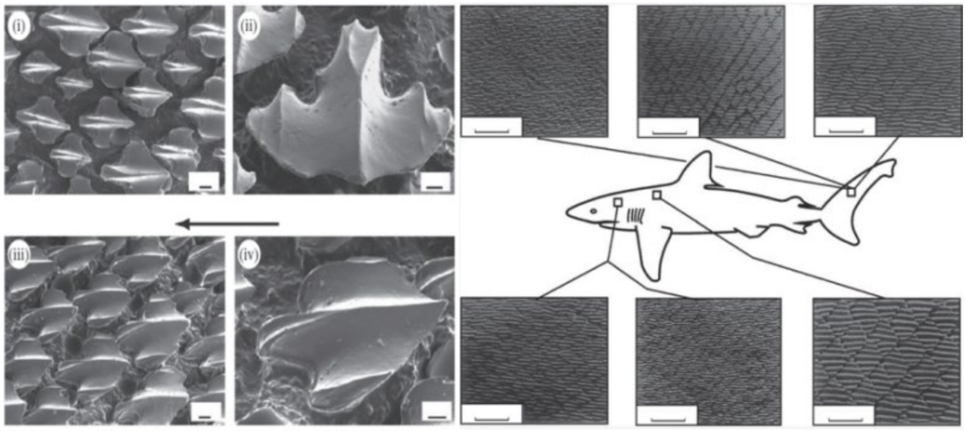

Figure 2. Microstructure of shark epidermis.

Based on the unique structure of the shark's skin, engineers have recently developed a variety of surface microstructures for aircraft fuselages with the aim of reducing frictional drag via ribbed surface protrusions or surface grooves.When a fluid flows over a smooth surface at a certain speed, the flowing fluid will, under certain circumstances, separate from the smooth surface and thus form a vortex. The resulting vortex will possess a certain speed in all other directions. Such a vortex will inevitably result in a degree of energy loss. Furthermore, in this chaotic flow field, the vortex with velocities in all directions will interact with the laminar fluid away from the plane, resulting in a larger range and number of vortices, and inevitably more energy and momentum loss. Due to the fluid's viscosity and the interaction between the fluid and the object's body, these vortices also significantly increase the shear stresses on the surface of the object, which has a significant drag effect when the surface area of the object is large.

In such a configuration, the fluid surrounding the object would only vortex at the top of the valley, because the high-speed vortex would only contact a small surface area near the tip of the rib, so only this area would be subject to high shear stress. Raising the vortex above the ribs greatly reduces the flow velocity of the fluid at the bottom of the valley, so the force between the liquid and the surface of the object in these areas will be greatly reduced, which plays a role in reducing drag. Figure 3 shows the situation where the above-mentioned surface microstructures form eddies in the flow field.

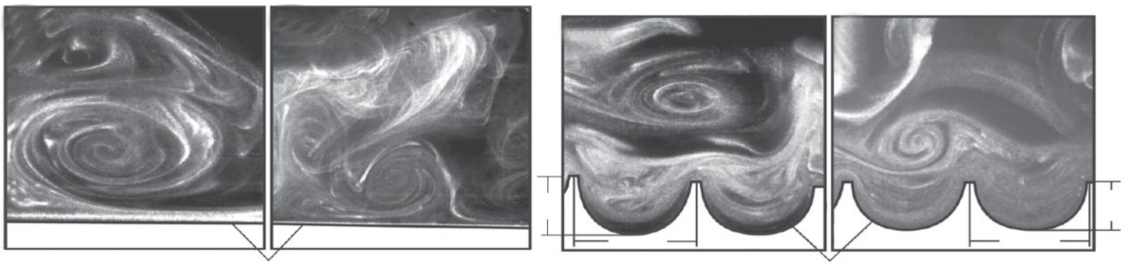

Figure 3. Flow direction vortex on the cross section of turbulent flows.

2.2. The principle of Induced Drag and Wingtip Devices

Induced drag, which is a component of all aerodynamic drag and occurs from pressure ratios balancing on finite wings, is another significant drag for aircraft. Due to the special structural design of the wing section, the air pressure under the wing will be higher than the upper surface of the wing, and the two airflows with different pressures will meet at the end of the wing. Due to the pressure potential energy of the gas, the gas below will Under the action of the pressure gradient, it flows to the low-pressure area on the upper surface of the wing, and the meeting and interaction of the two airflows cause a vortex at the end of the wing. Figure 4 illustrates the airflow near aircraft wing, and figure 5 illustrates the principle of vortex generation [18].

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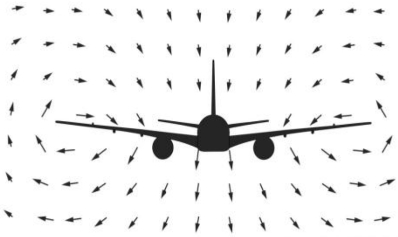

Figure 4. Diagram of air flow near the wing.

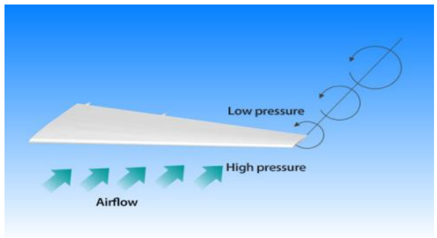

Figure 5. The principle of vortex generation.

According to Kroo, when a large civil aircraft is cruising, the drag generated at the end of the wing can make up about 30 to 40% drag force. Resulting drag during takeoff and landing can be as large as 80% to 90% [19]. Finding new, innovative ways to reduce drag and the accompanying fuel consumption is essential and desirable when the emphasis is on decreasing the environmental impact generated by aviation [19].

To reduce the induced drag, the most effective way is to use different wingtip devices, or "winglets", to redirect the wingtip airflow and weaken the magnitude of the wingtip vortex. Studies have shown that by installing winglets to the wing, the relative angle of the downwash will be reduced, minimizing the induced drag force [20]. Currently, researchers have tested and evaluated the performance of different winglets from comprehensive aspects. figure 6 shows the effect produced by adding winglets to the end of the main wing. And figure 7 describes the vorticity contour of the winglets.

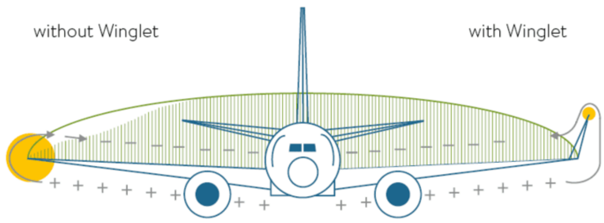

Figure 6. Diagram of the role of the winglets.

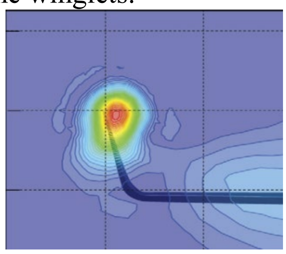

Figure 7. Vorticity contour of the winglets.

The last few years have witnessed a flurry of activity in the study of both passive and active winglets, as well as a variety of winglet/wingtip designs and geometries. Cheng and co. Winglets can have an effect on the vortex structure and, to a significant extent, its instability characteristics in addition to diminishing wingtip vortex strength. The installation of winglets reduces drag and rises the L/D ratio, which benefits the following factors: decreased fuel consumption, increased maximum takeoff weight and shorter takeoff distance, reduced noise, Improves the climb performance of the aircraft and reduces the strength of the wing tip vortices.

This review will focus on the split scimitar winglet, which is mainly installed on Boeing 737, one of the most popular narrow-body aircrafts in the world [21]. The split winglet features two blended winglets that are pointed in opposite directions. In this way, it can reduce the strength of the wingtip vortex by breaking it into two smaller vortices, which will dissipate energy faster and generate less downwash [22].

2.3. The principle of using adaptive lifting surface to reduce the profile drag

By evenly dividing the lift along each surface's span and between the lifting surfaces, induced drag is lessened. In recent years, adaptive lift surfaces have been extensively studied. In contrast to conventional non-adaptive surfaces, they can be individually designed and developed for specific conditions and use scenarios. And the shape of the wing can be changed according to the needs of the application. The efficiency of the rudder surfaces of the aircraft is affected by gaps between the rudder ailerons, flaps and the main wing on the wing. Therefore the concept of adaptive wing emerged. It adjusts the flow and aerodynamic loads on the wing surface by changing the geometric configuration of the aircraft wing in flight or by using flow control methods so that the aerodynamic forces are close to optimal for each flight condition within the entire flight envelope. This results in improved flight performance and reduced structural weight.

For passenger aircraft flying at subsonic speeds, skin friction drag is the drag that has the greatest effect on profile drag. To minimize the profile drag, the wing is always designed to reduce the air pressure in the direction of the airflow. It is beneficial to maintain laminar flow over the airfoil. Because laminar flow is a smooth, non-turbulent flow, this reduces drag and increases efficiency. Using adaptive lift surfaces such as trailing edges can increase the range of low drag. However, designers must limit trailing edge flaps to a small range of flap angles, and their design must be optimized to balance the benefits with the added weight and complexity. Using such a reduced induced drag approach to a tailless aircraft successfully resulted in a nearly circular lift distribution that is consistent with the traditional outcome of minimal induced drag [23].

3. Practical examples

3.1. Frictional drag on aircraft body surfaces

In recent years, serious energy crises and environmental pollution in China have become unsolved social issues due to the nation's rising consumption of fossil fuels [18]. Aerodynamic drag, which is directly related to a civil aircraft's energy consumption, is primarily pressure drag and friction drag in this context. So the search for a way to reduce the frictional drag on aircraft surfaces has been pursued. Nature has many biological evolutionary achievements that can be used for human reference. Sharks can swim fast thanks to the groove-like structure of their skin surface arranged in the direction of flow. This microstructure has been found to reduce surface frictional drag force in turbulent flows. With the rapid development of bionics in recent years, many research teams are also hoping to apply this technology to shark skin in aircraft.

According to research, shark skin has a ribbed structure rather than being a smooth surface. Dermal denticles, which are microscopic scales on the surfaces of shark skin, will keep them away from the surfaces, which keeps the water flow smoothly over shark skin [11].

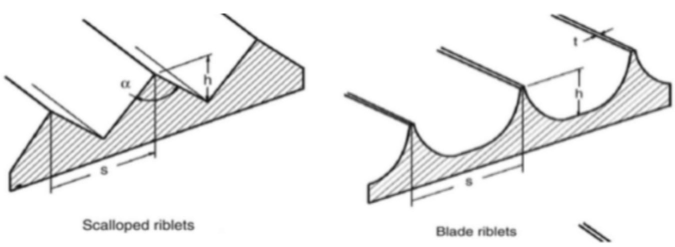

Figure 8. Different shapes of groove models.

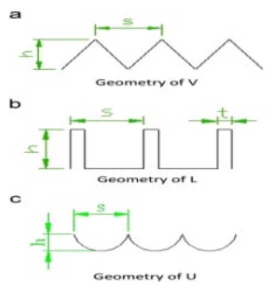

Figure 9. Different geometrical structures.

Figure 8-9 are the most well-known application of this technology in fluid engineering. Phelps participated in an all-around high-tech swimming suit while winning 14 gold medals at the Olympics in Athens and Beijing. There are many forms of fluid resistance. In the research of aircraft, there are two main resistances worth discussing. One is pressure resistance, and the other is friction resistance. In the case of aircraft, it can be minimized by constructing a streamlined shape, but frictional resistance reduction is far more challenging. On the surface, these vortices rotate and move simultaneously. They move naturally in the direction of lateral flow along the surface. The interaction of vortices with surfaces and the collision of neighbouring vortices during migration causes a degree of momentum exchange and kinetic energy loss, which is an important reason for the high frictional drag of fast-flying aircraft.

It has long been thought that objects with smoother surfaces will move with less drag. Indeed, a larger contact area does create more frictional resistance. However, when the dimensions of these riblets (groove microstructures) are sufficiently well designed, unexpected results can be achieved. A Korean research team concluded that when the eddy currents generated on the surface are lifted to the peak of the surface protrusions, the area of interaction between these eddy currents and the surface of the object will be greatly reduced, and most of the high-speed moving fluid will only interact with the surface. The small area at the tip of the rib interacts with each other, and the higher stress multiplied by the small area will greatly reduce the total resistance, while the large area at the bottom of the valley receives little shear stress, so the structure can make the frictional resistance suffered by objects in the flow field is greatly reduced [24]. A team from China has carried out a series of fluid simulation experiments based on this structure; Analysis indicate that the friction might be reduced by more than 12% when compared to a homogeneous surface [25].

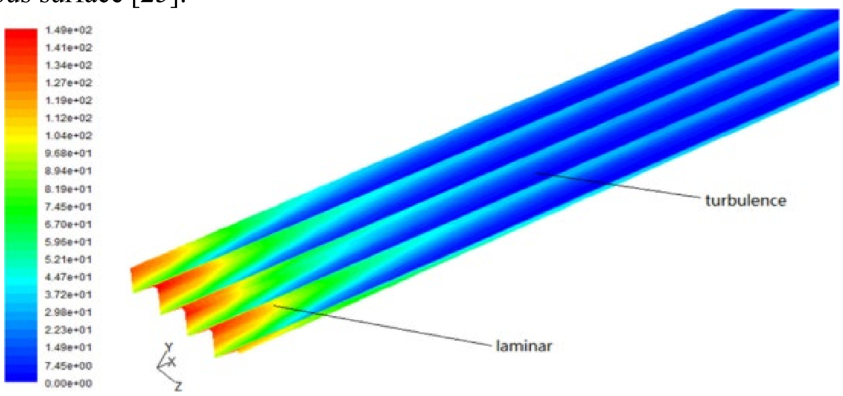

Figure 10. Stress simulation analysis of groove surface in flow field.

On this basis in figure 10, this microstructure was gradually applied to the surfaces of aircraft to reduce frictional drag. The A320 experimental aircraft's 70% surface received microgroove films from the Airbus Corporation, which led to a 1-2% fuel-saving benefit [26]. Riblet shapes that have been appropriately developed and produced can minimize friction drag by 7-8% [27]. These microscopic-sized structures can cover up to 70% of an airplane, which can result in 3% decreases in drag and fuel consumption [28]. Experiments in a wind tunnel have verified these results [29]. Examples of such structures that have demonstrated their aerodynamic effectiveness include an Airbus A340 that was in normal operations [30]. About 30% of the surface of this aircraft was covered with a structured sheet. It was proven that the airplane used approximately 1.5% less kerosene despite the film's added weight and the fact that it didn't completely cover the surface. An illustration of such a structured video can be seen in figure 11. (Image from a scanning electron microscope).

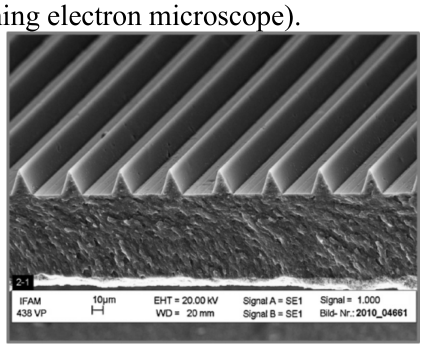

Figure 11. Example of a low-drag paint surface.

3.2. Induced drag and wingtip devices

One of the major drag forces acting on an aircraft is induced drag. When the plane moves at a certain velocity, the pressure difference between the upper and lower wing surface will generate a vortex at the wingtip [31]. After the horizontal airflow contacts the vortex, it will deflect downward to create a downwash airflow, which decreases the relative angle of attack. In this case, the lift force, instead of vertical to the ground, becomes vertical to the relative wind [32]. Therefore, the induced drag, a new force component, is created.

To reduce the induced drag, the most effective way is to use different wingtip devices, or “winglets”, to redirect the wingtip airflow and weaken the magnitude of the wingtip vortex. Studies have shown that by installing winglets to the wing, the relative angle of the downwash will be reduced, minimizing the induced drag force. Currently, researchers have tested and evaluated the performance of different winglets from comprehensive aspects.

This review will focus on the split scimitar winglet, which is mainly installed on Boeing 737, one of the most popular narrow body aircrafts in the world [21]. The split winglet features two blended winglets that are pointed in opposite directions. In this way, it can reduce the strength of the wingtip vortex by breaking it into two smaller vortices, which will dissipate energy faster and generate less downwash [22].

Compared with other wingtip devices, the split winglet has one of the most optimal performances when encountering different angles of attack. In the research conducted by Evan Cathers, split winglets, and other winglets, including blended, spiroid, raked, fence, tip sails, and naked wing, were installed on the two airfoils and tested in both computer simulation and wind tunnel with different angle of attack. In the simulation, winglets designed from ANSYS were tested in Computational Fluid Dynamics (CFD) software; in the physical experiment, 3D-printed 15-meter wings were tested in a subsonic wind tunnel.

	Blended	Raked Tip	Split Scimitar	Fence Tip	Spiroid	Tip Sails
2.5°	2.29	1.40	2.28	0.24	-0.93	1.11
4°	3.47	1.89	4.82	1.02	-2.39	0.21
6°	5.58	2.35	7.93	1.83	7.57	-2.27
8°	6.29	2.57	9.89	2.10	2.49	-2.90

Figure 12. Traditional Wing Simulation Efficiency (Cl / Cd Percent Improvement).

The test result in figure 12 shows the lift-to-drag ratio for each winglet. In figure 1, installed on conventionally cambered airfoil, the split winglet has the highest lift-to-drag ratio (L/D) ratio in all angle of attack(AOA) from 0 to 8 degrees, which covers the most frequent AOA during the take-off and climbing phases. However, the split winglet may not be ideal for supercritical airfoils. As the testing result indicates, the supercritical wing with a split winglet can only reduce drag efficiently at higher AOA. If the AOA is low, it may even decrease the L/D ratio by -8. 65%. Therefore, the split winglet can reduce drag effectively on a conventionally cambered airfoil but is inadequate for a supercritical airfoil. Beyond the split winglet’s general advantages and applicable scenarios, researchers also investigate the effectiveness of different split winglets by altering their parameters. A split winglet can be mainly modified in its cant angle and sweep angle (both upper and lower winglet should be considered).

Figure 13. Diagram of cant angle.

In the research conducted in NUAA as figure 13, Yunsong Gu et al. used a low-speed wind tunnel to test the vortex’s magnitude of blended, split, and no winglet on an aluminum NACA 23016 airfoil (conventional airfoil). Both blended and split winglets are tested by cant angles of 60 and 90 under 5, 10, 15, and 20 degrees of AOA. Instead of directly using the L/D ratio, researchers measure the static pressure at the center of the vortex with a seven-hole probe. According to the property of the vortex, the stronger vortex will have a lower static pressure coefficient.

Table 1. The static pressure coefficient in the core of wingtip vortex with/without winglets.

Winglet Type	Angle of Attack vs Static Pressure Coefficient			
	5°	10°	15°	20°
No Winglet	–0.20	–0.35	–0.56	–0.34
90° Blended	–0.06	–0.14	–0.22	–0.22
60° Blended	–0.04	–0.19	–0.33	–0.34
–60° Blended	–0.10	–0.18	–0.19	–0.19
–90° Blended	–0.10	–0.12	–0.14	–0.22
±90° Split	–0.07	–0.08	–0.11	–0.20
±60° Split	–0.12	–0.13	–0.21	–0.22

As shown in Table 1, the test results show that compared with blended winglets, split winglets (both 60- and 90-degree cant angle) perform better on weakening the vortex. Moreover, the split winglet with a 90-degree cant angle has a higher static pressure coefficient than 60 degrees, generating an even smaller vortex. In this case, since the vortex becomes weaker, the subsequent downwash will generate less induced drag. Overall, the split winglet is an effective method to reduce induced drag by dissipating the winglet vortex to the largest possible extent. Furthermore, this design avoids potential danger on small planes caused by vortex turbulence from large aircraft. It may also increase the takeoff frequency in major airports since vortices become weaker and need less time to evanish [17].

3.3. Adaptive lifting surface

In this section, the topic of discussion is the application of adaptive lift surfaces to mitigate air drag during flight. The authors put forward an optimization methodology for various surface configurations, taking into account trim constraints and using design variables such as incidence angle, twists, and flap angle. The objective is to make induced drag as small as possible while also considering profile drag, either with or without trim constraints. The three configurations proposed to facilitate aerodynamic analysis for optimized lift and longitudinal trimming. The primary focus is on this red paper adaptive lift surfaces.

For passenger aircraft flying at subsonic speeds, skin friction drag is the drag that has the greatest effect on profile drag. The wing is always made to reduce air pressure in the direction of the airflow in order to reduce profile drag. This helps to maintain laminar flow on the airfoil, which is a smooth, turbulence-free flow that reduces drag and boosts efficiency. The use of adaptive lift surfaces such as trailing edges can increase the range of low drag. However, the designer must limit the trailing edge flaps to a small range of flap angles and optimize their design to balance their benefits with the added weight and complexity. The Piaggio P180, an outstanding example of an aircraft with this usual design, has a trailing edge flap on the main wing that is managed by a flap track.

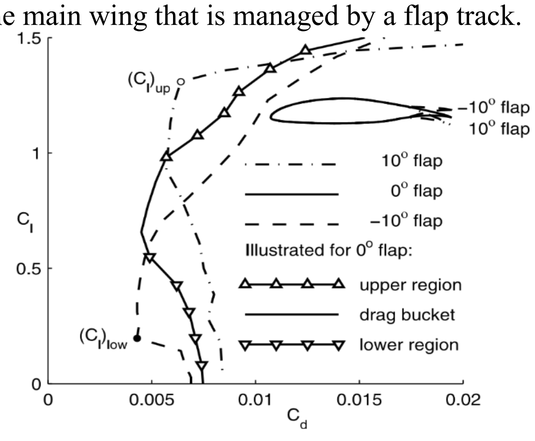

Figure 14. NASA NLF (1)-0215F airfoil with a trailing-edge (TE) flap.

The impact of a trailing-edge flap on the low-drag range of the NASA NLF (1)-0215F airfoil is demonstrated in Figure 14. This addition enables the airfoil to sustain a low drag coefficient over a broader range of lift coefficients. However, the figure reveals that the advantages of employing a trailing-edge flap are confined to a small range of flap angles, typically near the zero-lift angle. Furthermore, optimizing the design of the flap system can enhance the airfoil's performance significantly. The NASA NLF (1)-0215F airfoil is employed as an illustrative instance to showcase the impact of a trailing-edge flap on the airfoil's performance.

The Figure. 15 notes that using a flap angle between -10 degrees and +10 degrees can reach a low Cd, which allows for a Cl range from 0. 2 to 1. 3. The graph suggests that you can use linear interpolation to determine the flap angle required for any value of operating Cl between Cllow and Clup. By ensuring a smooth variation of the trailing edge flap angle with changes in operating lift coefficient, this approach will result in a reduction of the airfoil's drag coefficient and a more efficient performance.For method to find the minimum induced drag. The method outlined by the author enables the determination of flap and twist angles that lead to the lowest possible induced drag for an aircraft while maintaining a stable, trimmed condition.

To find the optimal angles, a method can be used which involves setting the first derivative of the induced drag to zero with respect to each flap/twist variable. This results in a N + 1 system of linear equations, where N represents the number of flap/twist variables, and can be solved to determine the optimal angles.

3.4. Comparison

The three articles compared in this analysis focus on different methods to reduce air drag on aircraft. The first article deals with applying adaptive lifting surfaces, specifically trailing-edge flaps, to minimize induced drag on subsonic airliners. The method used involves solving a system of linear equations to determine optimal flap and twist angles that minimize induced drag while satisfying trim requirements. The research scene consists in using the NASA NLF (1)-0215F airfoil as an illustrative example. The second article focuses on reducing friction on aircraft surfaces using shark skin microstructure and riblet surfaces. The research scene involves studying the principles of shark skin to develop a groove microstructure model that reduces surface frictional drag force in turbulent flows. The third article focuses on reducing induced drag using split scimitar winglets, which are installed on the Boeing 737. The method used involves testing various winglets using computer simulations and physical experiments in a subsonic wind tunnel to evaluate their performance. The advantages of each method are that the adaptive lifting surfaces can increase the range of low drag of an airfoil, the shark skin microstructure can reduce frictional drag on surfaces, and the split winglets can reduce induced drag effectively by breaking the wingtip vortex into two smaller vortices. However, each method also has its disadvantages, such as the added weight and complexity of the flap system, limited effectiveness in areas other than reducing frictional drag, and decreased lift-to-drag ratio at low angles of attack for certain airfoils.

4. Conclusion

This paper describes several drag reduction methods for modern subsonic airliners, analyzes their basic principles, evaluates their effectiveness based on previous studies and typical experiments, and emphasizes the importance of these three drag reduction methods. The report first examines the fundamentals of frictional, induced, and contour drag. It then discusses in detail the characteristics of the unique notch microstructure on the surface of the aircraft fuselage, followed by an analysis of the role of winglets at the end of the wing, and finally explores the role played by adaptive lift surfaces in drag reduction.

In terms of induced drag, in this essay, the function and fundamental ideas of wingtip winglets are discussed. The split winglet is characterized by two hybrid winglets pointing in opposite directions. This allows it to reduce the intensity of the wingtip vortex by breaking it into two smaller vortices, thus dissipating energy faster and producing less downwash. Current research demonstrates that by increasing the dissipation of winglet vortices, this approach effectively reduces generated drag. For airliners flying at subsonic speeds, skin friction drag is the drag that has the greatest effect on profile drag. To minimize profile drag, the wing is always designed to reduce air pressure in the direction of the airflow, which helps to maintain laminar flow on the airfoil because laminar flow is a smooth, turbulence-free flow, which reduces drag and increases efficiency. The use of adaptive lift surfaces, such as trailing edges, can increase the range of low drag.

The three approaches to reducing aircraft drag, fuel consumption and efficiency outlined in this paper have been extensively studied and applied in practical engineering. The world's major airlines and aircraft manufacturers are now committed to promoting these types of flight efficiency improvements to save energy and improve economic efficiency. The methods and principles of drag reduction outlined in this paper can be applied not only to civil airliners, but also to a wide range of fields such as automobile manufacturing, space technology, marine current engineering, oil and gas storage and transportation engineering. Of course, the application of these methods and theories in different fields needs to be further investigated and studied in the context of actual situations.

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