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# *Aerodynamic Optimisation of Aircraft Components for Fuel-Efficient Aircraft: Progress in Flaps, Winglets and Engine Configuration*

**Kaichen Shen**

*Bromsgrove School, Worcestershire, UK*
*kaichensapp@outlook.com*

***Abstract.*** With the rise in demand for fuel-efficient aircraft, many people have been exploring how to reduce aerodynamic drag to lower fuel consumption and emissions. The three main parts that affect the aerodynamics and fuel economy of the aircraft are flaps, winglets and engine settings. Aerodynamic mechanisms and Design Trade-offs of the different configurations have been studied in previous experimental and computational work. According to the required size of lift enhancement and flow separation control, the structure of the high-lift device for flaps will also be different. Although the aim of a winglet is to reduce induced drag, it may increase profile drag and other problems with the structure. The other is the arrangement of the nacelle and engine-airframe integration. Increase Propulsion Efficiency and Reduce the Effect of Aerodynamics. Based on the above analysis, it was determined that a single-component Design is not universally ideal. The overall goals of good aircraft design are to improve aerodynamics and structure, meet operational needs, and so on. In the future, with the development of advanced computational methods and multidisciplinary optimisation, the efficiency and sustainability of aircraft will continue to be improved.

***Keywords:*** Aerodynamic optimisation, aircraft components, fuel efficiency, interference drag

## 1. Introduction

Rapid development of the aviation industry has improved transport efficiency around the world, but at the same time, problems of fuel consumption and the environment have arisen. Operating an aeroplane has a large power demand, and aerodynamic drag is one of the main causes of fuel consumption. Therefore, the goal of many modern aircraft designs is to increase aerodynamic efficiency [1]. Decrease the aerodynamic drag and increase the lift-to-drag ratio to improve the fuel economy of the aircraft, reduce pollution, and extend the service life. Therefore, many people have been studying the reduction of drag on aircraft through various means, including changes in shape, control of airflow, etc.

Aerodynamic characteristics of an aircraft are determined by the combination of its shape and the air around it. A small change in the arrangement of components will significantly alter the pressure

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distribution and boundary-layer behaviour; thus, the general aerodynamics of the aircraft will change. In recent years, many of the design methods for airplanes have evolved from traditional empirical rules to sophisticated calculations and experiments, such as CFD and wind tunnel tests, etc. Therefore, the relationship among geometric parameters and aerodynamic performance can be quantified, and it is known how to modify the design to improve aircraft efficiency. Therefore, attention is being paid to the Design of components in the development of new, fuel-efficient airplanes.

Several parts of aircraft, such as flaps, winglets and engines, have attracted much attention in research because they significantly affect aerodynamics. Flaps are one of the more studied high-lift devices; they change the shape of the wing and thus affect the lift force at low speeds. The previous work has investigated how different types of flaps, flap deflections and other flap geometries affect the trade-off between increased lift and increased drag. CFD simulations and experiments have shown that, to improve the aerodynamic performance of flaps, the Fowler and slotted types can be used to control flow separation and increase the effective wing area [2]. Winglets are another type of aerodynamic feature that has also gained much attention in recent years, and they can reduce the induced drag caused by wingtip vortices [3]. According to previous studies, the geometry of winglets (such as height, sweep and cant angle) can affect the strength of vortices and aerodynamics. To increase the lift-to-drag ratio and reduce fuel consumption at the same altitude, the Design of the wingtip has been changed. Aerodynamics of engines has also begun to attract research attention; thus, the shape of the engine nacelle, fan size and installation position all affect airflow, interference drag and propulsion efficiency [4]. Many studies have examined the aerodynamic effect of various engine arrangements by observing how different designs of nacelles and engine-wing combinations change the aerodynamics of aircraft.

Although many studies have been conducted on the components of individual aircraft, most have focused on certain design features. The Design Strategy at the component level in a single aerodynamic optimisation framework has not been compared. As many factors affect the performance of aircraft, any improvement must be in harmony with the other factors. Therefore, the shape parameters and arrangement of flaps, winglets and engines will affect the aerodynamic performance and fuel consumption of an aircraft. According to the reasons for aerodynamics, optimisation methods and performance improvement, the previous studies have been classified. Challenges and Future Development Directions of Fuel-Efficient Aircraft are also mentioned.

## 2. Aerodynamic optimisation of aircraft components

### 2.1. Aerodynamic optimisation of flaps

Flaps are high-lift devices on an aircraft that are used mainly at low speeds, such as during take-off and landing, to increase the lift of the aircraft. They can change the curvature of the wing; in some cases, they can also increase the effective lift area and modify the airflow over the wing to alter the pressure distribution, lift magnitude and stall characteristics.

Young and others have studied the aerodynamics of high-lift systems and shown that flaps can change the circumferential lift and pressure distribution of a wing to increase lift and delay low-speed stall [5]. Flaps increase the lift but also increase the drag. Therefore, one of the goals of current research in aerodynamics is to improve the shape and geometry of flaps to increase lift while reducing drag.

At this time, the first studies were to quantify the performance of traditional plain flaps. For example, Kumar, M. S [6]. studied the basic lift-enhancing effect of clean flow. At an angle of attack

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of 0°, and without changing the aircraft pitch, the increase in the lift coefficient due to flap deflection from 0 to 5°, 10° and 15° is 0.335, 0.661 and 0.9701, respectively. Therefore, the flat flap will increase the lift at low speeds. Flow separation decreases the rise in lift of the straight flap. If the flap deflection angle is too large, the adverse pressure gradient at the wing surface will be relatively high; thus, it will be easier for the airflow to separate and pressure drag will increase. Straight flaps have a relatively simple structure but cannot control flow separation; thus, they have a relatively low high-lift performance, and many advanced high-lift devices have been developed to solve this problem to date, such as slotted flaps and fuller flaps.

Compared with plain flaps, slotted flaps can solve the problem of airflow separation at large deflection angles and thus improve the high-lift capability of the aircraft. The distance between the main wing and the flap directs the high-speed airflow from the bottom side of the wing to the top side of the flap. Increase the energy of the boundary layer in the airflow to improve its adhesion to the wing and thus achieve a larger deflection of the flap. In the experiments of plain flaps and slotted flaps at a fixed angle of attack of 12 degrees, the maximum lift coefficient of the plain flap is 2.38 and its deflection angle is 60 degrees. On the other hand, the maximum lift coefficient of the slotted flap is 2.73 and the deflection angle is 50 degrees [7]. According to experiments, the slotted structure can improve the adhesion of the airflow at the flap surface, and thus the maximum lift coefficient of a slotted flap is higher than that of a conventional plain flap. The shape of the slot, the angle of the slot and its overlap are also affected by aerodynamics. If the parameters are not set correctly, there will be an increase in disturbance drag and a decrease in the lift gain [8], so new high-lift devices have been continuously developed, such as the Fowler flap.

By improving the boundary-layer control of the slotted flaps, the fowler flap can be moved back and rotated downwards after deployment; thus, both the curvature and the effective lift area of the wing can be increased. Y Tian and his colleagues conducted an experiment to find that the maximum lift coefficient of the smooth cruise configuration is only 1.552, and after deploying the Fuller flaps, the maximum lift coefficients at the take-off and landing positions increased to 2.116 and 2.55 [9]. The top lift coefficient of a Fowler flap is higher than that of a plain or slotted flap. Since large commercial airliners need to produce a large amount of lift at take-off and landing and have low drag in cruise, Fowler flaps are widely employed on modern commercial aircraft. Complex Structures have high production and maintenance costs, and they are also heavy for the aircraft.

In short, the three kinds of flaps are for different purposes. The plain flap has a simple structure, but it is not very effective at increasing lift and is prone to flow separation. Although the Slotted Flap can increase the maximum lift of the boundary layer, it is more structurally complex. The Fowler flap is relatively high-lift, but it increases the curvature of the wing and the effective area at the same time; however, it is also heavier and has a more complicated mechanical structure. As shown above, the purpose of the design for modern flaps is no longer to increase lift; rather, now one must also consider drag, structure weight and system complexity.

## 2.2. Aerodynamic optimisation of winglets

When an aircraft wing produces lift, the pressure of the air below it is higher than the pressure above it. At the wing tip, the airflow on the high-pressure side is diverted around the upper surface of the wingtip and rotates to form a wingtip vortex; therefore, there is induced drag. Winglets can change the pressure distribution at the wingtip to reduce some of the energy in the wingtip vortex and thus decrease the induced drag caused by the vortex [10].

Previous studies have demonstrated that geometric parameters such as height, cant angle and sweep angle strongly influence the performance of winglet, among these parameters, winglet height

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is one of the most influential factors affecting aerodynamic performance. The crossover speed represents the flight speed at which the aerodynamic benefit obtained from induced drag reduction is equal to the additional profile drag introduced by the winglet, the balance point for the performance impact of winglets is determined by the crossover speed V $cr$ :

$$V_{CR} = \sqrt{\frac{2W}{\rho b}} \sqrt{\frac{-\Delta K(h)}{\pi \Delta h \bar{c} C_{Dp,WL}}} \tag{1}$$

Where denotes the reduction in the overall induced drag factor achieved by increasing height [11]. The primary benefit of increasing the height of the wingtip extensions is to reduce spanwise flow at the wingtips, thereby lowering the induced drag coefficient K(h). However, there are limits to how much aerodynamic benefits can be achieved by increasing winglet height. Larger winglets increase the wetted area and therefore the skin friction and profile drag. At the same time, higher aerodynamic loads on the winglet result in higher bending moments at the wing root, which require more structural reinforcement. The weight added to the airframe can negate some of the benefit from the reduction in induced drag. So, overly tall winglets will lead to diminishing returns and can decrease the overall efficiency of the aircraft.

Different wingtip devices have been used on modern commercial aircraft; thus, the design of winglets should be optimised according to the scale, purpose and operating environment of the aircraft. For instance, the Boeing 787 and the Airbus A320 family have different wingtip shapes and are thus more aerodynamically efficient. The Boeing 787 does not have the conventional vertical winglets; instead, it has raked wingtips and a large backward sweep. Extend the effective span and increase the distribution of spanwise lift in the Design to reduce wingtip vortices and cruise drag. It is not a conventional winglet, so there will be little additional interference drag and structural loss [12]. It is very suitable for the long-haul cruise ship. The Airbus A320neo has blended winglets called Sharklets that are smoother at the junction of the wing and the wingtip compared to previous designs [13]. Decrease the strength of the vortex and keep the additional structure simple to improve the fuel economy of narrow-body aircraft without adding much weight. According to the comparison of Boeing 787 and Airbus A320neo, the optimisation of wingtips is affected by the demands of flight and design. Raked wingtips can increase the aerodynamics of large, long-range aircraft, and blended winglets are more suitable for smaller planes that need to be light and compatible with airports.

## 2.3. Aerodynamic optimisation of engine arrangement

The main function of an engine is to produce thrust, but its arrangement in the airframe will also affect the aircraft's flight. Changes in the shape of the outside of the engine, such as the nacelle and wing-nacelle junctions, will affect airflow, pressure distribution and interference drag. Optimisation of the Engine Arrangement will improve the Aerodynamics of new aircraft and save fuel.

The shape of the nacelle affects the aerodynamics of aircraft engines and is relatively large for these engines. The start is to smoothly collect the air flow and reduce flow disturbance before the fan. Increase the size of the nacelle and fan, but this will increase aerodynamic drag. Although a relatively large nacelle can increase the propulsive efficiency by raising the bypass ratio, it will also increase the frontal area and wetted surface, thus raising the form drag and skin friction drag [14].

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Therefore, the change in nacelle diameter should be small enough to keep the increase in propulsive efficiency close to the loss of aerodynamic efficiency.

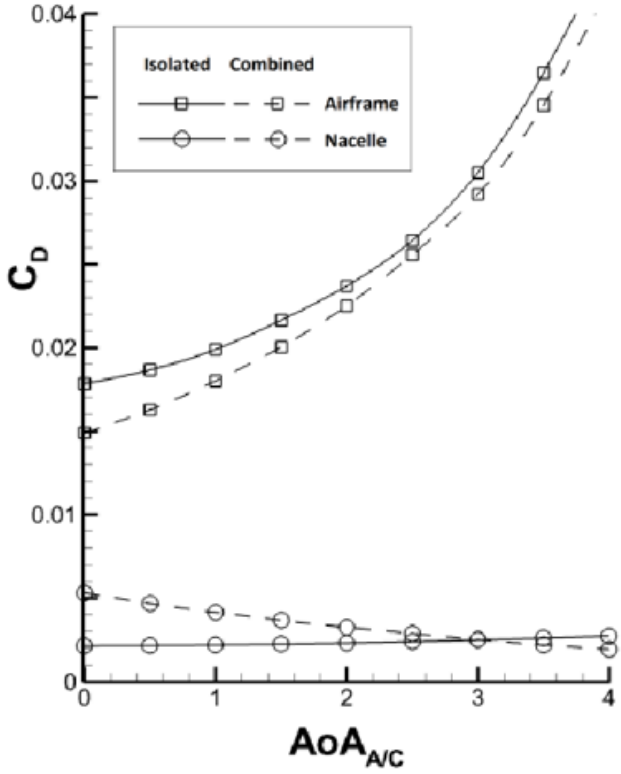



Figure 1. Aerodynamic drag trade-offs between airframe and nacelle configurations

The result shows the trade-off of placing the engine. Some configurations will increase the nacelle drag, but they can reduce the aerodynamic penalty of the airframe. For example, it was found that the maximum aerodynamic gain of about -29 drag coefficients for the airframe and the maximum penalty of about +32 drag coefficients for the nacelle are shown in Figure 1. Therefore, the optimisation of engine placement should consider the joint effect of nacelle and airframe interaction rather than looking at these two parts independently [15].

Another Reason for the shape of the nacelle is where to place the engine. The two general arrangements of civil aircraft are underwing and aft-fuselage mounting. Mounting Schemes modify the airflow environment around the nacelle, change pressure distribution, induce interference drag, etc. Airbus A320 is a typical representative of modern aircraft with underwing engines. The above have good load transmission, are convenient to maintain, and have a high-bypass turbofan engine. However, there is a small space between the nacelle and the wing, so engineers need to move the nacelle and change the strut design.

Most regional jets, such as the Embraer E-Jet series, are located at the back of the main body. The engine is far from the front of the main wing, so there is less disruption to the air flow over the wing. At the same time, strengthen the structure of the rear fuselage; otherwise, it will be too light and structurally weak.

Therefore, the optimisation of engine configuration is not to achieve an all-round excellent installation method, but rather to select one that is most suitable in terms of aerodynamics, structure and operation.

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## 3. Conclusion

Aerodynamic optimisation of the flap, winglet and engine installation parts is to be carried out to reduce fuel consumption and improve overall performance. Flap systems show that to increase the high-lift effect, one must also increase the drag. Although the first type of flap is relatively simple and effective, it will likely separate flow. Although slotted and Fowler flaps are more elaborate and have a higher lift coefficient due to better control of the boundary layer and an increase in effective wing area, they are also relatively heavy and structurally complex.

Winglet optimisation means that to reduce induced drag, one needs to consider both shape and aircraft purpose. A larger winglet is needed to reduce the strength of the wingtip vortex, but it will also increase the weight and profile drag of the structure. That is why different solutions at the wingtips, such as raked wingtips and blended winglets, are selected according to the size and operating conditions of the aircraft.

In other words, aerodynamic efficiency of an engine arrangement is not only determined by the performance of the engine but also by its integration with the airframe. The Geometry of the Nacelle and Engine Mounting Position will affect interference drag and airflow. According to the list of various mounting methods, none is particularly superior to all others for all aircraft.

Aerodynamic optimisation is indeed a multi-disciplinary concept, and it includes all kinds of aerodynamics, structure and operation. In the future development of aircraft, all-encompassing optimisation will need to be carried out to improve CFD methods, experimental verification, intelligent design, etc., in order to reduce fuel consumption and pollution.

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