



# The Influence of Flap Angle Adjustment on Lift and Drag Characteristics in Aircraft Performance

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**Abstract.** This paper explores the aerodynamic implications of flap angle adjustments on aircraft performance, with a focus on optimizing lift and drag characteristics during critical flight phases such as takeoff and landing. Trailing-edge flaps, including plain, slotted, Fowler, and Gurney flaps, are examined for their roles in modifying wing geometry to enhance lift or manage drag. The study investigates how different flap angles influence airflow, pressure distribution, and boundary layer behavior, using both computational fluid dynamics (CFD) simulations and real-world applications in commercial and military aviation. It highlights specific aircraft, such as the Airbus A320, Boeing 737, and C-17 Globemaster III, showcasing advanced flap systems tailored for efficiency and stability. Furthermore, the study discusses the operational challenges in material durability, maintenance, and certification, as well as emerging trends such as morphing flaps and AI-driven adaptive control. Overall, the research demonstrates how intelligent flap angle management contributes to safer, more efficient, and environmentally sustainable flight operations.

**Keywords:** Flap Angle Adjustment, Aerodynamic Performance, Lift and Drag Characteristics, High-Lift Devices, Aircraft Efficiency

## 1 Introduction

Achieving the best overall aircraft performance is simultaneously a complicated and a complicated goal in modern aeronautical engineering. This goal is dependent upon closely regulating the aerodynamic forces acting upon the aircraft; of these forces, the main ones are aerodynamic lift and drag, which must be highly balanced to create the most effective aircraft performance, stability, and safety! This balance is most critical in taking off and landing when the aircraft is most vulnerable. When taking off or landing, the speed of an aircraft is relatively slow; it will need a large amount of lift in a short length of runway as opposed to the faster speeds at which it can produce lift; furthermore, the aircraft may have limited time to obtain the amount of lift required. This means careful use of high-lift devices that are incorporated into the aerodynamic control surfaces, of which the major and more vital category is trailing-edge flaps. The trailing-edge flaps have an angle of deflection and potential for the pilot to more actively change the wing shape of the aircraft by changing the airflow over the wings

of the aircraft to obtain additional lift or to change the drag to achieve the required flight condition [1].

Flap angle not only relates to stability and manoeuvrability, but flap angle for a pilot will also pertain to addressing two rising challenges in the current aviation industry: high fuel burn and environmental responsibility. With air travel demand rising globally, stakeholder concerns are also escalating in the aviation industry's impact on the environment, especially related to greenhouse gas emissions from fuselage and fossil fuel consumption. Aerodynamic inefficiencies and fuel burn levels, particularly at low speeds, with the collection of flap undercarriage contributing to fuel emissions [2]. Optimal fuel burn levels and increasing regulatory and social pressures to reduce carbon emissions in aviation provide an opening to prioritise aerodynamic performance of the flap undercarriage with financial incentives supporting an aerodynamic priority and an environmental push.

This paper examines the effects of flap angle adjustment on lift and drags properties, discusses the potential aerodynamic influences on flap performance, and includes incidence angles of nearly all flap types found on commercial and military aircraft, as includes as several case studies, computational studies, and in-flight data. The goal is to determine how improving the flap angles can optimise the total aircraft efficiencies, minimise fuel usage, and support sustainable aircraft design. This paper aims to broaden the understanding of how effective aerodynamic engineering can aid in future efficient and sustainable air travel.

## **2 Types of Flaps and Their Role in Aerodynamic Performance**

Since their first deployment in aviation, flaps have come a long way. Originally envisioned simply as a hinged surface for use during takeoff and landing, they now exist in hundreds of different configurations that are complex, multi-component systems that can be used for a variety of aircraft and mission profiles. Today, a wide array of flap configurations is employed across the aviation industry, each offering unique aerodynamic advantages. The most common types include plain flaps, split flaps, slotted flaps, Fowler flaps, and Gurney flaps. Each type plays a specific role in modifying wing geometry and manipulating airflow to increase lift or induce drag, depending on the flight phase [3].

Plain flaps are the most basic design, rotating downward from the trailing edge of the wing to increase camber and, consequently, the lift coefficient. They are simple, lightweight, and easy to manufacture, making them ideal for small aircraft. However, their effectiveness is constrained by early flow separation at high deflection angles, which leads to increased drag and potential stall [4].

Split flaps consist of only the lower surface deflecting downward, leaving the upper surface unchanged. While this configuration produces a significant amount of drag, it does not offer as much lift enhancement as other designs. Nevertheless, split flaps are useful in landing scenarios, where increased drag can help shorten the landing roll [2].

Slotted flaps represent a major improvement in flap design. By incorporating a gap between the wing and the flap, they allow high-pressure air from below the wing to

flow through and energise the boundary layer over the flap. This helps delay flow separation, increases lift, and improves the overall lift-to-drag ratio [2].

Fowler flaps further extend the wing rearward before deflecting, increasing both surface area and camber. This combination is highly effective in generating lift. Wind tunnel experiments on the GA(W)-1 airfoil showed that Fowler flaps could raise the maximum lift coefficient ( $C_{lmax}$ ) to 3.8, far higher than what plain flaps can achieve, especially when flap deflection, slot gap, and overlap are optimised [5].

Finally, Gurney flaps offer a minimalist but effective approach. These small vertical tabs placed at the trailing edge modify the pressure distribution and wake characteristics of the airfoil. Studies have shown that Gurney flaps can elevate lift curves by approximately 0.3 in  $C_l$  with relatively minor drag penalties, making them a popular retrofit for UAVs and lightweight aircraft [6].

### 3 Mechanisms of Lift and Drag Variation Through Flap Angles

The aerodynamic performance of an aircraft wing is largely defined by two forces: lift and drag [7]. Lift is generated by the pressure difference between the upper and lower surfaces of the wing, while drag is the resistance encountered as the wing moves through air. Adjusting the flap angle directly affects both forces by altering the wing's effective camber and angle of attack [1].

When flap angles increase, so does the lift coefficient, as more airflow is directed downward and the upper surface experiences lower pressure. However, this also increases induced drag, which arises from lift generation itself, and parasite drag, which results from the enlarged frontal area and turbulent wake [2]. The relationship between lift and induced drag is nonlinear. While moderate increases in flap angle (typically  $10^\circ$  to  $20^\circ$ ) produce favourable lift-to-drag ratios, further increases (above  $30^\circ$ ) often lead to rapidly increasing drag with diminishing lift returns.

Computational Fluid Dynamics (CFD) simulations of plain flaps on a NACA 0012 airfoil indicate that the optimal flap deflection angle lies between  $15^\circ$  and  $25^\circ$ . Beyond this range, airflow separation becomes significant, and drag rises sharply [8]. Similar studies on Gurney flaps show that while they do not require angle deflection, their height plays a similar aerodynamic role. When properly sized—approximately 1.25% of chord—they generate beneficial trailing-edge vortices that stabilise the wake and delay stall onset [5].

Flap angle also affects the pitching moment and longitudinal stability of the aircraft. Increased flap deflection tends to pitch the nose downward, which must be compensated for by elevator input or automatic trim systems. In advanced military systems like the C-17, automatic adjustment systems monitor angle of attack, engine pressure ratios, and airspeed to restrict excessive flap angles that may induce deep stall conditions [9].

At the core of flap effectiveness lies a complex interplay between boundary layer behaviour, flow separation, and pressure distribution. Increasing the flap angle changes the stagnation point location and causes the flow over the upper wing surface to accelerate further. This produces a stronger suction peak, contributing to greater lift.

However, this same acceleration makes the boundary layer more prone to separation, especially when the energy in the layer is insufficient to stay attached to the steep surface curvature.

Advanced CFD simulations show that, as flap angle increases, a strong leading-edge vortex often develops in high-lift configurations, particularly with multi-element airfoils. This vortex helps reattach flow downstream, temporarily staving off stall. However, if the angle increases beyond a threshold, typically around  $40^\circ$  for Fowler flaps, the vortex detaches, leading to massive flow separation and loss of lift.

In military applications, such as on delta-wing aircraft or fighters, where high agility is needed, control surfaces akin to flaps are sometimes used in conjunction with canards or elevons to actively manipulate vortices and pressure gradients. While the mechanisms differ, the principle remains: altering surface geometry (including flap angle) changes the flow path and controls lift and drag production across the airframe [8].

## 4 Real-World Applications in Civil Aviation

Modern commercial aircraft depend heavily on advanced high-lift systems to maintain safety, control, and efficiency during low-speed flight phases. Among these systems, trailing-edge flaps—particularly multi-slotted Fowler flaps—are indispensable. These devices are engineered not only to enhance lift but also to manage drag across varying flight conditions, such as takeoff, climb, descent, and landing. Aircraft like the Airbus A320 and Boeing 737 exhibit sophisticated flap systems that take advantage of multiple angles, which allow the pilot to adjust the aerodynamic performance relative to the demands created by each flight segment [4].

The Airbus A320 is one of the most significant models for short to medium-range commercial aviation, with significant aerodynamic research on improvements to enhance efficiency and minimise noise. The A320 was incorporated into the European Smart Morphing and Sensing (SMS) project, which was concerned with morphing technologies focused on the trailing-edge flap at the rear of the aircraft. These morphing flats enable continuous active morphing. The morphing flaps can flap quickly and gently to reduce the unsteady aerodynamic influence. Evidence based on numerical simulations and external experiments concluded that dynamic deformation could offer up to 3% increase in lift, around crucial combinations of flight, such as approach and landing phases, and less noise, especially important for noise-regulated airports in metropolitan areas [6].

In terms of operational utilisation, flap positions are selected based on various factors, including aircraft weight, length of runway, and environmental influences. On takeoff, flaps are used at 1 or 2 settings (approximately  $10^\circ$  -  $15^\circ$  of lift) to maximise lift while minimising drag. When landing, a flap setting of 3 or full extension (approximately  $30^\circ$  -  $40^\circ$ ) can be applied to further maximise lift and provide a slower and steeper descent path. Time-Resolved Particle Image Velocimetry (TR-PIV) testing demonstrated that the IAWD A320's morphing flaps provide broader, smoother flow

distributions and reduced wake thickness and drag, which also enable reduced noise emission [4].

The Boeing 737 uses a similar flap system, with roughly similar staged options for deflection. This is, for instance, for short field takeoffs, where  $5^{\circ}$ - $10^{\circ}$  flap angles are used for takeoff, allowing for plenty of drag to be induced for a safe landing and deceleration. Ideally, a descent slope of  $40^{\circ}$  is preferred for a safe descent. Operational data collected across airlines globally suggests that drag could be managed with flap angle efficiency to achieve better performance enhancement, improved component life, and reduced fuel consumption, for ecological and commercial savings.

## 5 Military Aircraft Applications: The C-17 Globemaster III

Military aircraft frequently expose themselves to much more demanding and complex environments than commercial aircraft, which requires advanced aerodynamic systems to perform robustly in a range of, and sometimes extreme, conditions. A military aircraft must be capable of short takeoffs and landings (STOL), operate from unprepared runways, carry heavier payloads, and manoeuvre agilely during its tactical mission. To enable military aircraft to fulfil these requirements, advanced high-lift systems, including multi-element flap systems, are found on military programs.

C-17 Globemaster III, a large military transport plane developed by McDonnell Douglas, is an example of a military plane with an advanced flap system. The C-17 features a very redundant and responsive flap control system for quick strategic airlift of soldiers and goods. This system includes multi-slotted Fowler flaps and full-span leading-edge slats, which are necessary to produce the high lift required for takeoff and approach with heavy weights and at slow speeds [9].

The C-17 uses a complex digital fly-by-wire (FBW) control system that allows real-time flap angle adjustments based on flight parameters, unlike conventional aircraft. To select the proper flap setting, the flight computer looks at things like the angle of attack, the thrust from the engine, how the weight is placed, and the speed of the plane in the air. It was determined by the professionals that some flap deflection angles would result in a deep stall condition, more so at any kind of CG loading on the test flights of development flights. And the nose-up attitudes were hard to change by hand. To address this problem, an Angle-of-Attack Limiting System (ALS) was installed on the C-17 [9].

In operation, on the C-17, flap angle choice is not all about achieving max lift; the aircraft has to keep pitch stable and retain control over the plane too, whether it's an engine failure or steeply plunging into a tight landing space. The plane's flight tests record and its work on the field show that its combination of a strong mechanical body and cleverly made control instructions gives it fantastic safety levels for every kind of plane flight [9].

Military planes need dependability, stamina, and aerodynamic correctness to finish operations, so lively, smart flap systems are needed. The C-17's system shows how flap angle control can work as part of a bigger plan to handle how an aeroplane flies. It tries to always put safety and getting where you're going first, no matter what happens when flying conditions change.

## 6 Expanded Design and Operational Issues

Flap system using material science, computational intelligence, and mechanical durability to achieve the ability to work under different types of flight conditions is not an easy thing to do. Need to work well with modern flight control software, be able to handle large aerodynamic forces, and be anti-fatigue. There are many forms of Fowler flaps, which are particularly remarkable in their engineering. They use track mechanisms that slide rearward and then pivot down, thus increasing wing area as well as camber. Especially when it is moving at a high speed (and retracts), they experience an unceasing mechanical loading (and air-dynamic drag). Therefore, they have to be made of materials that are very strong for their weight, and which never break even when used hundreds of thousands of times.

An airline has a very strict schedule to observe and to guard things like the flap track and hydraulic piston, hinge, and a small sensor because the flap is very important for flight safety. System has any irregularities might lead to non-synonymous placement or failure, which is quite dangerous on takeoff and landing. So, condition-based tracking and maintenance are needed to make it work reliably and fly as expected [2].

Implementing new or more effective cover designs, such as installing Gurney flaps, is challenging for aircraft that are already in service. Even relatively simple modifications must be thoroughly validated through wind tunnel testing, full-scale flight trials, and computational fluid dynamics (CFD) calculations. These steps must be followed according to aviation regulators' recommendations to prevent instability, shop behaviour changes, or structural pressure amounts. Despite their obvious advantages, Gurney flaps, while simple in concept, can have an impact on airflow characteristics that necessitate re-certification, slowing the adoption rate [6].

Reliability is a crucial factor in systems engineering. In military software like the C-17 Globemaster III, designers incorporate mechanical backup systems that can manually operate the wings [9]. Although this adds weight, it ensures vision consistency in challenging or hazardous environments where digital systems may fail. Minimising weight is a top priority in business aviation, where effectiveness and gas economy are important. This has resulted in the use of innovative composite materials with lower size, such as carbon fibre-reinforced polymers, which are more durable. Also, they are using Smart Materials and embedded sensors for real-time health monitoring of flap systems so as to enable Predictive Maintenance and improve overall Safety [4,5].

The advanced flap system at last still has to strike a balance between aerodynamic benefits, the government's demands, and operating expenses in the long run.

## 7 Future Prospects and Emerging Innovations

Aviation continually alters, reacting to growing power needs and environmental mandates, and the future of flap systems dwells between superior materials, real-time computing, and bio-motivated design. And also, one very good future is to use AI and data processing during the flight. Flap Angle Settings were originally set once and then

manually chosen by the pilot at certain points in the flight. But AI-driven adaptive systems will be able to make flap angles adjusted continually based on the flight conditions at this time. Can track the current air speed, altitude, the weight of an aircraft, and turbulence meteorological. Variables to set flaps to the most efficient. At the moment, Machine learning would also allow these sorts of systems to learn from past flights as well, picking out the best deflection profiles based on the results of previous flights through similar situations [5].

And these technologies apply to certain kinds of transportation too, like the kind of urban air mobility that's emerging as part of electric vertical takeoff and landing planes, eVTOL planes. These vehicles are designed to work in crowded cities, which makes everything very small, quiet, and uses less power. These aeroplanes see traditional hinge flaps being replaced by pure morphing surfaces, adjusting their airfoil all by shape alone. Piezoelectric or SMA actuators built into the wing surfaces of composite wings can be used to make the surface flex like a bird wing would. This can offer both aerodynamic as well as mechanical, noise, and maintenance advantages [6].

From the environmental perspective, a better flap system can do a lot for reducing emissions and acoustic pollution. During descent, the higher the flap angle, creates more wake turbulence and noise are created due to the fast-moving air being slowed and separated off. The morphing flaps with optimization of curvature that can smoothly change curvature, will keep the flow somewhat smoother, but not smooth, less "disrupted," and with even less drag, with even somewhat more lift: That is, quieter and cleaner operations, both of which matter more and more as aviation ventures into populous areas [9].

As regulations continue to implement stricter noise and emission limits, especially as they are closer to urban areas like airports, we think flaps should be smart and able to adapt. Innovations in this sector go beyond performance; it is about creating a sustainable, responsive aviation design where every last aerodynamic surface is smart, efficient, and environmentally friendly [6].

## 8 Conclusion

Lap angle regulation was always an important part of creating improved aerodynamics, which can make for both safer and efficient flight. Through the increase of the effective camber of the wing and changing the airflow behaviour on an airfoil, a flap can help the aircraft obtain greater lift at low speeds. That ability is extremely useful for takeoffs and landings, etc., at relatively low speeds, and some spaces are more constrained. But there is a cost for the aerodynamic advantage. Increase in drag, change of pitch stability, complex structure, and regular maintenance. These are all design and operational-related issues.

This essay has analysed the impact of varying flap angles on lift and drag from both theoretical and practical angles. In looking at different flap types like Plain, Slotted, Fowler, and Gurney flaps. Different flap type has different levels of aerodynamic performance and mechanical efficiency. Aircraft such as the Airbus A320 and Boeing 737 have shown how flap angle control is applied in the real world with a commercial

airliner, and the C-17 Globemaster III shows the importance of flap angle control in military operations, where it's important for versatility and reliability.

The aviation industry's efforts to make cars use less fuel, decrease emissions, and follow stricter rules about making less noise are leading to an important role for advanced flap systems. Innovations in morphing wings, AI-driven adaptive control, and lightweight materials will be set to define what's feasible for aerodynamic surfaces. Whether it is a complex multi-slotted flap on an airliner or a simple passive Gurney flap on a small drone, intelligent management of the flap angle will be needed to get the best performance possible.

Ultimately, flaps are more than just mechanical appendages, and they adapt; they are a responsive tool for a constantly changing set of goals in flight—efficiency, safety, sustainability.

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