

A Review on Wingtip Devices for Reducing Induced Drag on Fixed-Wing Drones

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Abstract- This review paper presents and analyzes previous studies on wingtip devices mainly to reduce induced drag on fixed-wing aircraft and drones. Some of the parameters discussed are the different types of winglets, cant angles, and adjustable wing structures. And these are compared against performance measures including reduced drag, fuel consumption, and improved endurance. This study aims to explore the optimized design of a wing that will give maximum drag reduction for fixed-wing drones, including the use of Gurney flaps and optimized winglets design. Optimised wingtip devices greatly affect the overall performance of fixed-wings. Better optimised performance of drones can have much better payload capabilities, endurance, and increased agility. They can have special capabilities like flying at higher altitudes and perform more sophisticated maneuvers. It is hoped that through this review paper, future studies on improved performance of fixed-wing drones will be performed with the help of computational fluid dynamics tools such as MachUp, Aeolus Aero Sketch Pad and Ansys.

Keywords – Induced drag, fixed-wing drones, wingtip devices, endurance, maneuverability, optimization

I. INTRODUCTION

Research and applications of unmanned aerial vehicles (UAVs), commonly known as drones, are a developing area of study as their technology is getting better in terms of reliability and performance [1-4]. Their use has gradually increased over the years and replaced the use of manned aircraft like helicopters because they offer a flexible, accurate, and affordable solution to some of the technical challenges. They are used for nature conservation monitoring and for animal identification [5-6]. Some of the advantages of using drones are that they can cover a large area for surveying at a lower cost, they use less fuel, cheaper to operate because they enable lower investment in features that ensure the safety of the onboard pilot [7]. Long-range drones are also used in the military to conduct patrols and anti-poaching operations, and sometimes sent for long-range missions in countries like Afghanistan and Iran [8-11].

For industrial use, they are used for monitoring overhead transmission lines and in photogrammetry [12-14]. There are growing interests to have delivery drones, for potential medical delivery and door-to-door parcel delivery by companies like DHL express, Google, and Amazon [15-17]. In the agricultural sector, they are many applications that drones are used for including using them for pest control and crop production [18]. The robotic bees are under research to make robots that mimic flying bees to address the looming crop pollination. The robotic drones are to be used to replace bees to pollinate crops, more details are in [19-20]. Figure 1 shows some of the applications of drone technology.



Figure 1. (a) Delivery drone [21], (b) robotic bees [22], (c) military drone [23] and (d) fumigation drone.

However, drones also have some disadvantages, they would invade people's privacy and fly at highly restricted areas like airports, sometimes causing flight disruptions. They have the potential to crash and cause harm to people and their surrounding, hence precautions should be taken when handling and operating them [24-25].

II. TYPES OF DRONES

Drones are classified according to their design configurations, the rotor-wing, transitional and fixed-wing drones [26-27]. Fixed-wing drones rely on their main wings for lift while rotor-wing drones depend on propellers for both lift and forward motion. The motion of rotor-wing drones is controlled by speeding or slowing multiple downward thrusting motors [28].

Fixed-wing drones their performance is affected by aerodynamic parameters and physical conditions such as wing design, altitude, wind forces, and payload distributions [29]. One of the advantages of fixed-wing drones over rotor-wing drones is that they have better stability and control [30, 31]. They can be fitted with autopilot to autonomously takeoff and fly longer distances and land [32, 33]. They can be controlled to fly in a group by decentralized cooperative behavior, which implies that each drone in a group can act accordingly to the mutual interest of the group. Multiple fixed-wing unmanned aerial vehicles (UAVs) can be used to cooperatively track an uncooperative and moving target [34-38].

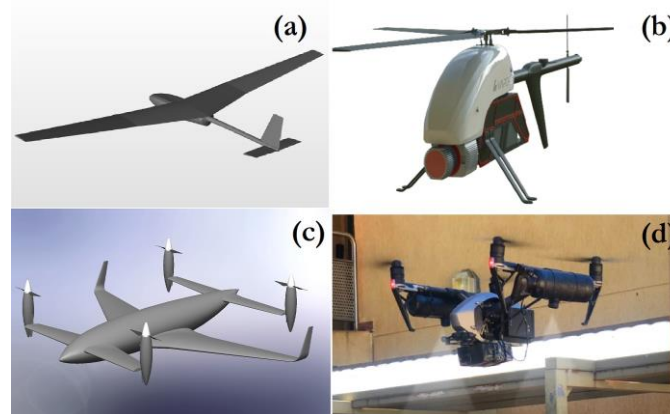


Figure 2. (a) Fixed-wing drone, (b) single-rotor drone, (c) tilted-rotor and (d) multi-rotor drone.

Figure 2 (a) is a fixed-wing drone that uses a wing to provide lift, it can fly at high altitudes and has more endurance and range than all other types of drones. Figure 2 (c) shows the single rotor has a greater efficiency over multi-rotor. It can be powered by a gas motor for even longer endurance, and it is mostly used for spraying crops with pesticides due to its ability to hover. Multirotor drone as shown in Fig. 2 (d) is commonly used for aerial photography, it has limited endurance and speed [39]. According to this research, another type of drone that is gaining popularity and is optimized to perform better than both rotor and fixed-wing drones is the transitional drone. Transitional drones have both characteristics of a rotor-drone and fixed-wing drone. The tilted-rotor and hybrid drones are both transitional drones, they were developed such that they can take-off and land vertically (VTOL). A tilted-rotor drone is shown in Fig. 2 (c) rotates its rotors vertically to produce downward thrust during takeoff and landing, then tilt its rotors 45 degrees to direct thrust horizontal and backward for cruise flight, more details can be found in the studies [40-42].

III. DESIGNING A FIXED-WING DRONE

From previous studies, the design requirements to consider when designing fixed-wing drones include drone range, payload, take-off and landing distance, maneuverability, and speed requirements. During the conceptual design stage, sketches start with an approximate sketch of the following wing design, wing configuration, fuselage sizing, tail geometries, engine, and material selection [43].

Fixed-wing drones are controlled by balancing aerodynamic forces and moments for stability and maneuver [44-46]. Their control surfaces or control inputs are mounted on the trailing edge of the wings for roll, yaw, and pitch movements. The control surfaces are ailerons for roll angle, elevator for pitch angle (up and down), throttle for motor speed, and rudder for yaw angle (left and right). The fixed-wing drone uses its main wing for lift, and it can fly at high altitudes over 300m where it's usually difficult to manually control a drone as explained in the study [47]. Other known fixed-wing drones can fly at about 4700 m above sea level like the eBee drone [48]. Flying-wings are mostly used for aerobatic flights, they perform loops, rolls, and other feats of spectacular flying performances.

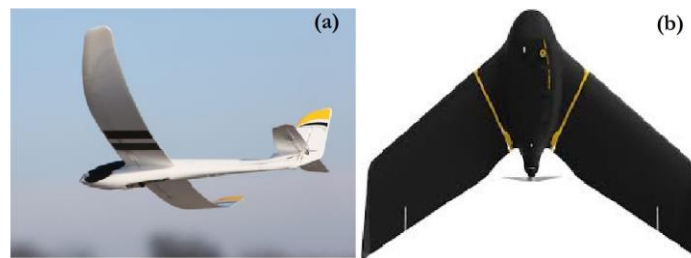


Figure 3. (a) Motorised Sailplane [49] and (b) Ebee [48].

For the longest flights, motorised sailplane design is the best choice of design. They can glide and stay longer on air even after power failure [49-51]. Figure 3 (a) and (b) both show the sailplane and the Ebee drone respectively.

3.1 Wing Design

Drone/aircraft wings are designed based on mission profile, other factors to be considered in designing the drone wings are altitude, payload, speed, agility, and lift-to-drag ratio [52]. However, the fuselage design, sizing, detailed wing design, and practical steps in the design process are out of the scope of this review. The review will focus on wing design and optimization. Some computer-aided design software, such as Aeolus ASP, Ansys fluent [53], MachUp5 [54], and SolidWorks [55], are used to assist in aerodynamic calculations, analysis of forces and moments on the wing. They also perform structural analysis, simulations and allow to optimize model parameters such as wing shape or flight conditions. Figure 4 shows two widely used software, Fig. 4 (a) shows a wing simulated on SolidWorks software, and Fig. 4 (b) shows a wing designed using an aerodynamic design application for UAVs and light aircraft called Aeolus ASP.

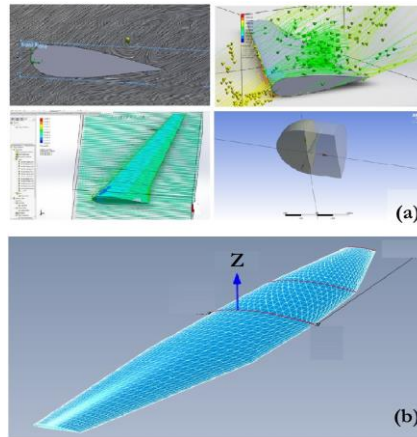


Figure 4. CFD simulations performed during wing design.

3.2 Aerodynamic Lift and Drag

Aerodynamic force is exerted on an aircraft body by a stream of air or other fluids in which the body is immersed, it is due to relative motion between the body and the fluid. When an airfoil or drone wing is moving relative to the air, it generates aerodynamic forces called lift and drag. They are resolved into two components that are acting through the body's center of pressure [56]. Figure 5 shows these forces acting on an airfoil, together with weight and thrust.

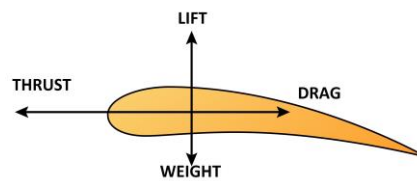


Figure 5. Aerodynamic forces on an airfoil

Lift is the force component perpendicular to the direction of motion and drag is the force component parallel and opposite to the direction of motion [57].

3.3 Airfoil

An airfoil is the cross-sectional shape of a wing or a lifting surface and it is subjected to aerodynamic forces. It is a prerequisite to the satisfactory performance of the lifting surface. The selection of an airfoil is the most critical part of designing an aircraft wing. There are many airfoil coordinates found on the UIUC Airfoil Coordinates Database site about 1,600 [58, 59]. When designing a wing a 2D airfoil is selected from the database like the one shown in Fig. 6.

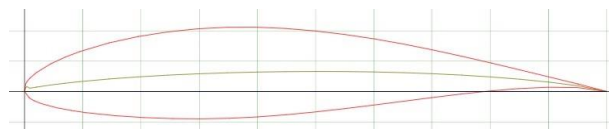


Figure 6. Airfoil from UIUC airfoil database [59].

The database gives detail of the airfoil like the Reynolds number and aerodynamic parameters. The most used are symmetrical, semi symmetric, and stepped airfoil. For optimization of a wing, this review will focus on the semi-symmetric airfoils because they produce more lift at a given angle of attack than symmetric and stepped airfoils. They have an improved lift-to-drag ratio and better stall characteristics. The commonly used symmetric and asymmetric airfoils on drones are the NACA0015 and NACA63612 respectively. Figure 7 shows 3D wings made from two commonly used airfoils, symmetric and asymmetric [60-61].

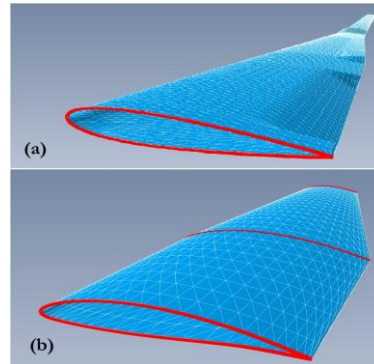


Figure 7. (a) Symmetric airfoil NACA0015 and (b) Asymmetric airfoil NACA63612

A wing with a symmetrical airfoil has zero lift at zero degrees angle of attack while asymmetrical airfoils generate some lift at even zero angles of attack [62, 63].

3.4 Angle of Attack

Lift is generated when a wing is angled to the upcoming airflow as shown in Fig. 8 below. The airflow on the upper side of the wing accelerates and creates a low static pressure, while the airflow on the lower side of the wing decelerates and creates a high-pressure zone. This difference in pressure on the upper and lower sides of the wing causes lift.



Figure 8. Airflow around an airfoil.

The lift coefficient of an airfoil varies with the angle of attack. The increase in angle of attack is associated with an increase in lift coefficient up to maximum value, after which lift coefficient decreases. As the angle of attack increases, separation of the airflow from the upper surface of the wing becomes very noticeable, leading to a reduction of the rate of change of the lift coefficient. A higher angle of attack means more induced drag, when the wing is at the zero angle of attack there are no vortices, and this will result in lower induced drag [64, 65]. The effects of angle of attack on induced drag on will be investigated further in this review.

3.5 Wing Planforms

Most fixed-wing drones have the main wing and a tailplane also known as a horizontal stabiliser. The main wing is the main lifting surface while the tailplane provides stability and control. It helps adjust changes in the position of the center of pressure or center of gravity caused by changes in speed, altitude, fuel consumption, and payload.

Types of drone wings can be classified according to their shape, position, and number of wings attached to the fuselage. The shape can be elliptic, rectangular, delta, trapezoidal, closed wing, etc. They can be mounted at different positions on the fuselage, i.e., low-wing, mid-wing, shoulder-wing, high-wing, and parasol-wing.



Figure 9. PBX-6A is an amphibious aircraft that uses parasol wing [Picture taken by the first author].

Figure 9 shows an Australian amphibious aircraft that uses a parasol-wing, it is a wing that is not directly attached to the fuselage but held above by pylon or struts. According to [66, 67], its positioning on the fuselage affects aerodynamic performance and structure.

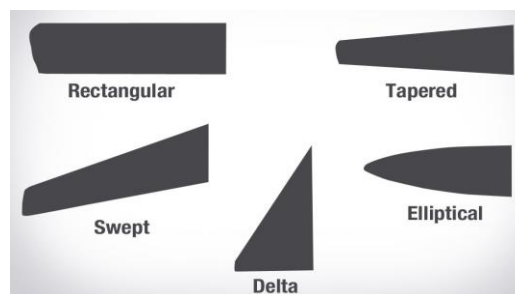


Figure 10. Aircraft wing planforms.

Figure 10 shows aircraft/drone wing configurations, delta wing is a low aspect ratio wing and is mostly used for supersonic aircraft. The delta wing is strong structurally and is also easy to manufacture and maintain. Tapered wing narrows towards the tip, they are aerodynamically more efficient than a rectangular wing. There are different types of tapered wings such as the trapezoidal wing, which is commonly used in early supersonic aircraft. It provides low aerodynamic drag at high speeds while maintaining high strength and stiffness. A rectangular wing is considered to be the most structurally efficient wing and is mostly used on low-speed aircraft. The elliptical wing has the leading and trailing edges curved such that the chord length varies elliptically with respect to span. It has the least amount of drag but it is difficult to build compared to a rectangular wing. Another commonly used wing is the swept wing that is used on large commercial jets and has low drag at transonic speeds like the Boeing 787 Dreamliner [68, 69].

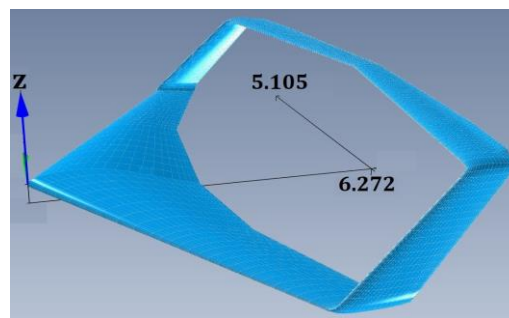


Figure 11. Diamond Joined-Wing Configuration UAV designed with Aeolus ASP.

Aircraft manufacturers are currently working on the diamond-joined wing configuration as shown in Fig. 11. It is a new technology under investigation to be used not only limited to drones but also for commercial passenger aircraft. However, the main challenge is the weight and complex structure [70].

This wing configuration increases maneuverability and is less prone to stalling especially at high angles of attack during subsonic flights. The configuration increases the aerodynamics efficiency due to its potential lower induced drag but is also much heavier, due to heavy wings [70, 71]. Table 1 shows the summary of these wing planforms.

Table 1. Characteristics of Wing Configurations.

Wing Planforms	Aircraft	Advantages	Disadvantages
Elliptical	Supermarine	Most efficient Low drag	Poor maneuverability Difficult to make
Rectangular	Piper PA 38 Piper J-3 Cub	Easy to manufacture Cheap to build	Aerodynamically inefficient
Tapered	P-51 Mustang	Improved maneuverability and efficiency, Good structurally and easier to make than elliptical wing	less efficient than elliptical wing
Delta	Dassault Mirage 2000, Concorde	Most efficient in all flight regimes (subsonic, transonic, and supersonic); Improved wing loading and maneuverability	At low speeds it has high drag It needs high AOA to maintain lift
Trapezoidal	Combat aircraft, e.g., F-22 Raptor	High performance configuration, Efficient at supersonic flights Very good stealth characteristics	Reduced maneuverability
Sweptback	Commercial aircraft, e.g., Boeing 787, Hawker Hunter	Reduced drag at transonic speeds	Not easy to control
Closed wing	Used on old aircraft, e.g., Bleriot IV, Hawker Hunter	Stiffens the structure and reduces aerodynamic losses at the wingtips	No significant aerodynamic advantage over other wing platforms, It increases the total weight of the structure

3.6 Aerodynamic Optimization of a Wing

A critical design consideration in any aircraft or drone is its three-dimensional wing shape. After the conceptual design phase, different design configurations are chosen based on their estimated performances. The wing design will further be optimised to achieve desired performance. Engineers use Computer-Aided Design (CAD), Computation Fluid Dynamics (CFD), and FEA software and wind tunnels to optimise the wing. When designing an aircraft wing, several fluid dynamic concepts are considered, the two most important ones are lift and drag, which corresponds to a wing's ability to fly the aircraft. During a wing design, engineers always try to minimize drag and increase lift. The main goal is to have a higher or favourable lift-to-drag ratio. This is because reducing drag and increasing lift leads to better fuel economy for an aircraft, glide ratio, and climb performance as explained in [72-74]. The higher the lift-to-drag ratio the longer the endurance of the aircraft or the drone.

3.7 Wake vortices

All aircraft generate wake vortices also called wake turbulence; the vortex wake start as a vortex shed from the trailing edge of the wing. When an aircraft is flying, there is an increase in pressure below the wing and a depression on the top of the aerofoil. Therefore, at the tip of the wing, there is a differential pressure that triggers the roll-up of the airflow aft of the wing to form wingtip vortices [75,76]. Limited swirls exist at the trailing edge of the wing, and they form trailing edge vortices as shown in Fig. 12. Vortices reduce the air pressure along the entire rear edge of the wing,

which increases the pressure drag on the airplane. The energy required to produce a vortex comes at the expense of the forward motion of the airplane [78, 79].

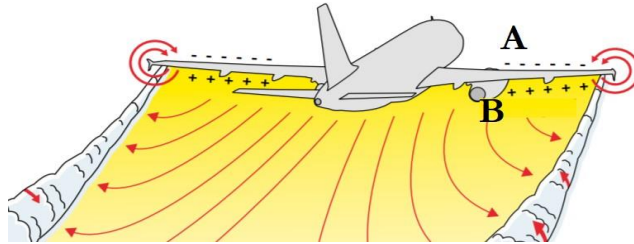


Figure 12. Wake turbulence generated from an aircraft; region A is of low pressure while B is high pressure region [77].

There have been significant developments to improve wing performance by introducing trailing edge devices such as Gurney flaps and serrated trailing edge. According to studies, Gurney flap is a small tab projecting from the trailing edge of a lifting surface. Typically mounted perpendicular to the pressure-side of the surface of an airfoil. It increases the maximum lift coefficient, but at a low angle of attack, it also increases drag coefficient [80, 81], although for thick airfoils drag reduction has been reported [82]. Based on boundary layer thickness, a correctly sized Gurney flap can achieve a net benefit in the overall lift-to-drag ratio. Studies have also shown that attaching a serrated panel to the trailing edges of a lifting surface could give a higher coefficient of lift at constant chord Reynolds number according to [83]. Gurney flap and serrated trailing edge can be combined on a wing to further improve lift and drag characteristics of a wing, more detail can be found in [84, 85]. Fig. 13 below shows both the Gurney flap and serrated trailing edges of an aircraft wing. The size of a Gurney flap usually ranges from 1 to 5% of chord according to [86, 87].

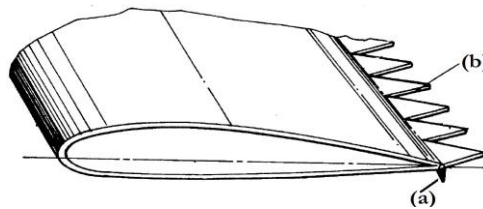


Figure 13. (a) Gurney flap and (b) Serrated trailing edges [86].

3.8 Lift-induced Drag

According to [88] induced drag also called drag due to lift, as previously explained, is generated when there is a considerable pressure difference between lower and upper surfaces of a wing, tip vortices are produced at the wingtips. These tip vortices will then swirl up and get around the local edges of a wing as illustrated in Fig. 14. This phenomenon will reduce the lift at the wingtip [89]. Induced drag is the strongest when the wing is generating more lift because the air pressure difference between the bottom and top of the wing will be very high [90, 91].

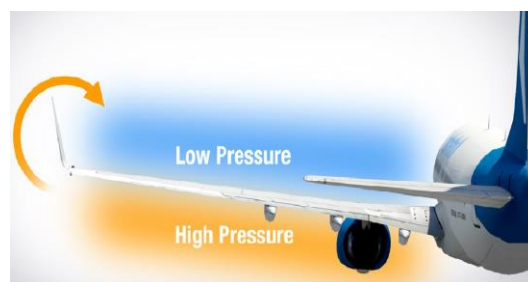


Figure 14. The pressure imbalance causes higher-pressure air below a wing to spill up over the wingtip into the area of lower-pressure air above [92].

According to [93, 94] for a planar wing with an elliptical lift distribution, induced drag can be calculated as shown in Eq. (1) however, the induced drag is further divided by the span efficiency factor for a non-planar wing with an elliptical lift distribution [95, 96].

$$D_i = \frac{L^2}{\frac{1}{2}\rho V^2 \pi b^2} \quad (1)$$

where

L is the lift force, V is true airspeed, b is the wingspan, and ρ is the air density.

Induced drag can also be expressed in terms of drag and lift coefficient:

$$C_{D,i} = \frac{D_i}{\frac{1}{2}\rho V^2 S} = \frac{C_L^2}{\pi AR} \quad (2)$$

where, S is the wing reference area, AR is the aspect ratio as in Eq. (3)

$$AR = \frac{b^2}{S} \quad (3)$$

and lift coefficient can be calculated as

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} \quad (4)$$

According to Eq. (1), induced drag is a function of wingspan and flight speed. It decreases with an increase in wingspan and flight speed. As indicated in Eq. (2), an aircraft with a high aspect ratio has better performance than one with a small aspect ratio. Extending the span would lower the lift-induced drag, but would increase the parasitic drag, weight, and weaken the structure. Lift Coefficient is a function of angle of attack, therefore an increase in the angle of attack leads to an increase in lift coefficient [97], hence according to Eq. (2), it increases induced drag [98]. Lift coefficient can be expressed as in Eq. (4). So during takeoff and landing at low airspeeds but at a high angle of attack the wingtip vortices are very strong and induced drag is very high [99]. As the aircraft climbs higher the air becomes thinner, as such at cruise altitude the aircraft travels faster but needs a high angle of attack to maintain level flight. The wingtip vortices will be stronger hence more induced drag.

IV. WINGTIP DEVICES

Over the years many investigations have been carried out to ways to diffuse strong vortices produced at the wingtip by not increasing the aircraft wingspan [100]. They were trying to improve the aerodynamic performance of an aircraft by using wingtip devices thereby optimising the span-wise lift distribution [101]. This review, it will focus in detail on the use of wingtip devices to optimize the wing performance of a subsonic-speed aircraft. The wingtip device was first proposed by Endplate theory in the early 20th century that theoretically a vertical flat endplate added to the wingtip could reduce induced drag. The theory was patented by Frederick W. Lanchester, British Aerodynamicist in 1897, but his theory was a disappointment in practice because it failed to produce a net benefit. During cruise, conditions increase in the viscous drag overwhelmed the reduction in induced drag more than offsets the saving in induced drag [102]. In 1976, Whitcomb at NASA inverted a winglet [103], he was inspired by birds such as eagles and stork, he noticed that gliding birds that soar through the air had their feathers upturned at their wingtips as shown in Fig. 15. The individual feathers in the slotted tips resemble the winglets used on the wingtips of some aircraft to reduce induced drag.



Figure 15. Eagle with its feathers upturned at their wingtip [Photo credit: Jim Zipp].

Engineers have been working to improve wingtip devices from endplate theory by coming up with different designs that will keep the profile drag low and improve the overall efficiency of the wing. They came up with different types of winglets, winglets are small, nearly vertical lifting surfaces, mounted to the wingtips [104]. They work by reducing wingtip vortices forming on top of the wing as illustrated in Fig. 16. This would be beneficial for both operators and aircraft manufacturers by saving a lot of money spent on fuel [88, 105].



Figure 16. Wingtip vortices formation on a wing with and without a winglet.

4.1 Types of Wingtip Devices

Several types of wingtip devices are currently used on aircraft and drones, they function in different manners, but their intended purpose is to reduce the aircraft's drag by partial recovery of the tip vortex energy. The selection of the winglet device depends on the specific situation and airplane type [106]. Fig. 17 shows some of the inventions of the winglets and wingtip devices used on modern airliners.

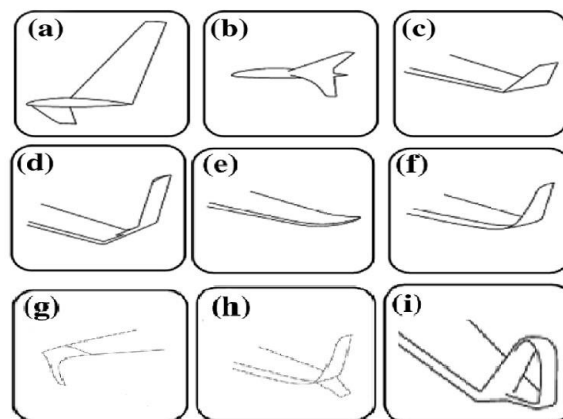


Figure 17. Different types of winglets and wingtip devices, (a) Whitcomb winglet, (b) tip fence, (c) canted winglet, (d) vortex diffuser, (e) raked tip, (f) blended winglet, (g) drooped winglet, (h) blended split and (i) spiroid winglet [107, 108].

Wingtip devices come in different sizes, shapes, inwards, and upwards angles because they are critical for correct performance. Wingtip devices at the end of the wing not simply horizontal but vertical are regarded as winglets or

sharklets as Airbus calls them [109]. Raked wingtips however are not vertical and are widely considered as winglet variants. Blended winglets, wingtip fences, raked wingtips, and canted winglets are commonly used wingtip devices on modern aircraft including biplanes [110]. Blended wingtips are the most popular winglet used by Airbus, Boeing, Bombardier, Russian Tupolev, etc. They were first used in 1990 on the McDonnell Douglas MD11 aircraft. They reduce interference drag by reducing any induced vortex from a sharp intersecting angle of a join [111]. They are used on medium/long-range flights like on Boeing 737 NG and Boeing 757 because longer flights mean longer cruising and that means most of the fuel is saved. Wingtip fences are one of the simplest wingtip devices, they extend both above and below the wingtip. They were used in older airlines back in the 1980s. They are preferred by Airbus and featured on most of their aircraft family including the A380. Raked wingtips are the most recent winglet variant, they are best described as integrated wingtip extensions. They have a higher sweep than other wingtip devices. They effectively increase the wing's aspect ratio as well as reducing induced drag thus making them more efficient than most wingtip devices. They are said to improve fuel economy, shorten takeoff field length and climb performance [112, 113]. Canted wingtips are shaped such that they help expand the lifting surface of the wing and are used on Boeing 747 aircraft.

Several studies are currently performed by engineers over various winglet configurations. Such as the spiroid winglet, folding winglet, variable cant angle winglet, fluidic winglets, and the morphing winglets [114-116]. According to a recent study carried by W. Garvey [117], and another by K. Dhileep et al. [118], spiroid winglets are not just intended to reduce wingtip vortices but to eliminate them completely. Should the new spiroid winglets successfully eliminate wingtip vortices, it will be a boost in fuel savings and efficiency by over 30% to existing blended winglet designs [119, 120]. From the literature it was established that a well-designed High Aspect Ratio Wings (HARW) have better aerodynamic performances due to reduced induced drag. However, there are limiting factors to having an aircraft with a longer wingspan, such as ground infrastructures for taxing and parking and wing strength [88]. For that reason, aircraft engineers are now considering folding wings that will have a high aspect ratio for lower induced drag and better fuel efficiency as shown in Fig. (18). Boeing 777-X to be the first passenger aircraft to use folding wings [121-123]. Morphing winglet is another promising solution, it has the potential to increase aircraft performance. It can change shape under different flight conditions to provide additional aerodynamic benefits for the entire flight [124, 125].

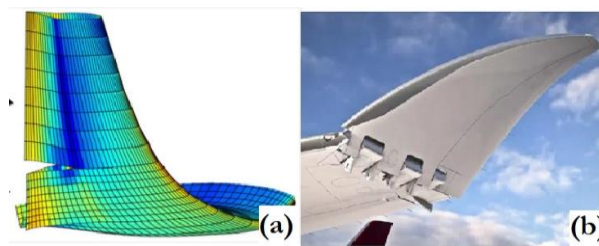


Figure 18. Concepts winglet design; (a) morphing winglet [126], (b) folding winglet [127].

Winglets do not operate effectively under all conditions throughout the flight envelope, but they form a permanent feature hence, offering additional skin friction drag and mass. They are more effective during cruises, landings and take offs. Engineers are more optimistic to use a winglet that can be present only when a need arises by trying the new concept of using fluidic Winglets [128]. For a fluidic winglet, a controlled stream of air will be injected in the span-wise direction towards the wingtip as shown in Fig. 19. It will create an aerodynamic force strong enough to discourage the wingtip vortex formation [129, 130].



Figure 19. Fluidic winglet on a wing [130]

4.2 Design of a Winglet

There is a trade-off when using winglets to improve aircraft performance as the wetted area of the wing increases hence an increase in profile drag. Profile drag is caused by the wing section, angle of attack, or shape of the airfoil. Winglets slightly increase the total weight of the aircraft and skin friction drag due to air moving along a surface of a body. Pressure drag also increases due to flow separation from the imbalance of pressure acting over the front of the body not equal to the one acting at the rear. The following geometries of a winglet need to be considered to avoid structural compromise of the wing, avoid causing wing flutter, and wing stall [131, 132]. Figure 20 shows key parameters that describe the shape of a winglet [133]. Winglet height: It is determined by the optimal induced drag and profile drag relationship.

- Winglet airfoil: The goal is to have a winglet that will generate enough lift while maintaining the lowest possible drag.
- Chord distribution: The sizing of the winglet is very important if it is too big, it will cause high winglet loading and could make a wing stall prematurely. If the airfoil chord distribution is too small it will require a large lift coefficient.
- Toe angle: It is the mounting angle, controls overall loading on the winglet.
- Twist: it tailor the load distribution.
- Cant angle and curvature radius

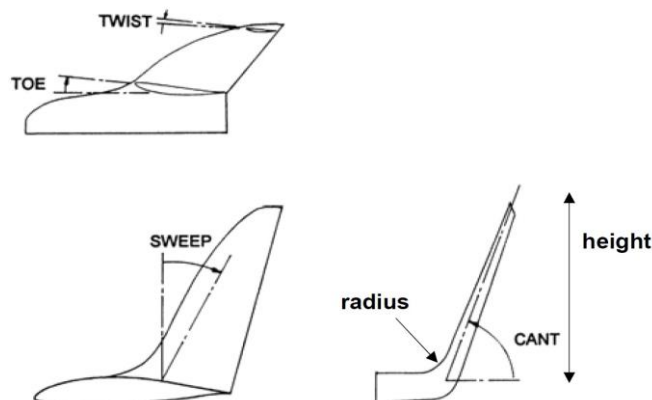


Figure 20. Winglet design key parameters [133].

4.3 Winglets Design and Optimization for Unmanned Aerial Vehicles (UAVs)

Many studies have been conducted to prove that winglets improve the overall efficiency of a large aircraft flying at subsonic speeds, however winglet designs for UAVs are largely unproven. From literature, it has shown that induced drag is a function of true airspeed, at high flight speed the winglets become more effective and reduce vortices generation. However, UAVs operate at very low speeds and Reynolds number. It is for the interest of this study to find out what other engineers or researchers have done to optimize their performance by reducing induced drag. R. Dagur et al. experimented to find out the effect of winglets on a flying wing UAV. The UAV used a blended wing and was simulated at a low Reynolds number of about 3.8×10^5 and the velocity was set at 15 m/s. It was discovered that there was a drag reduction of 2.1% and 1.64% at 4° and 8° angle of attack respectively when compared to the same UAV without winglets [134, 135]. Blended winglets were also designed and tested for Medium-Altitude-Long Range-Endurance (MALE) UAV. The calculations showed a considerable improvement in aerodynamic performance of the UAV and increased total flight time by approximately 10% [136]. J. Metrinho et al. developed a variable-span morphing wing for a small UAV and experimented to investigate its performance. It was discovered that near its maximum speed it was possible to obtain a 20% wing drag reduction compared to a fixed-wing [137].

V. SUMMARY AND ANALYSIS OF WINGTIP DEVICES

This review mainly discussed wingtip devices, their design, aerodynamic performance, and their offsets. The winglets from the analysis vary with the design, height, and shape and they depend on the airfoil and aircraft type. Flight conditions, angle of attack, and airspeed greatly affect the performance of different types of winglets.

Table 2. Performance Analysis of Winglets

Winglets	Aircraft	Performance measure	Effectiveness	References
Blended winglet	MALE UAVs, Falcon 2000, Boeing 757 Boeing 767	Reduces fuel burn up to 4%	Reduces interference drag at the winglet junction	[110, 138]
Spiroid winglet	Gulfstream 11 Jet	Reduces fuel burn up to 10%	Eliminates concentrated wingtip vortices	[119, 120]
Canted winglet	Boeing 747-400's, Airbus A340 Airbus A330	Increases range by 3.5%	Increases lifting surface of the wing to reduce induced drag	[110]
Raked tip	Boeing 787-8 Boeing 777-200	Reduces drag by 5.5% Improves fuel efficiency	High aspect ratio to diminish tip vortices	[112]
Wingtip fence	Airbus A320, A380 Antonov An-148	Improves fuel efficiency	Reduces tip vortices	[110]
Folding winglet	Boeing's 777-X	Maximize fuel efficiency	Folds wingtip to comply with airport regulations Wingspan can increase by 7m to maximise drag reduction	[121-123]

Table 2 present a summary of wingtip devices, their performance measures extracted from the literature review. The results from Table 2 present the theoretically and experimentally proven solutions from a wide range of research. According to Table 2, blended winglet is mostly used winglet both on UAVs especially on MALE UAVs and on aircraft. They are easy to make and most effective during cruise for long flight missions. Spiroid winglet are still under investigation and according to engineers it will effectively eliminate the induced drag and improve fuel consumption by 10% compared to other wingtip devices. Folding winglet however its main purpose is to expand the wingspan for maximum drag reduction and maximize fuel efficiency on the new Boeing 777-X aircraft. There are benefits and limitations brought by wingtip modifications. The main purpose of the wingtip devices is to improve lift-to-drag ratio by reducing induced drag, improve take-off and landing performance, and range as indicated in Table 2. Another aim of using wingtip devices is to decrease turbulence formation behind an aircraft by reducing wake vortices.

There are some limitations associated with the use of each of the winglets. Blended and canted winglets increase the weight of the wing, increase the wing-root bending moment and they are costly to build. The future research direction in blended and canted winglets can be focused on using new composite materials with reduced weight and comparable strength.

The Spiroid winglet is mainly used for jets aircraft, it is very costly due to the complexity of the wing and winglet construction. It also increases parasite drag due to an increase in wetted area and increases skin friction drag. The future research direction can be about 3D printing of composite material to address the complexity of the winglet construction. This can significantly reduce the cost associated with its construction.

The raked winglet reduces drag by 5.5% and improves fuel efficiency but it also increases the weight and wingspan of the wing. The future research direction is about using composite materials with reduced weight without compromising strength. Because the wingspan is increased significantly a foldable raked winglet can be an option. A folding winglet is very expensive to build because of its complex structure, it will be costly for maintenance. It also compromises the structure of the wing and increases the total weight. The future research direction on folding winglets can be about the manufacturing of moving components such that they become more durable and modular with almost zero maintenance requirements.

VI. CONCLUSION

Wingtip devices can reduce wingtip vortices that cause lift-induced drag. Avoiding the formation of vortices at the edge of the wingtip, improves flight performance of an aircraft, medium-range, and long-range UAVs with regards to fuel consumption, flight range, enable additional payload capability, and reduce community noise. By reducing fuel consumption means a reduction in Carbon dioxide and Nitrogen oxide emissions. Morphing wings or variable cant angle winglets are considered for optimizing the aerodynamic efficiency for all flight conditions.

In this study, the formation of vortices and induced drag have been extensively studied including the benefits and offsets of wingtip devices. The future direction on improvement of wingtip devices is to come up with a winglet that will maximise the performance of an aircraft and UAVs for all flight conditions. Morphing winglets and adaptive winglets are the future state-of-the-art type of winglets to be used to meet the maximum performance requirements for future aircraft and UAVs. Some of the limitations of using wingtip devices are the increase in weight and the wingspan of the wing. The fluidic winglet is a proposed solution to replace winglet structure, it will disrupt the formation of the tip vortex without a physical increase in the wingspan and weight.

The use of Gurney flaps and wingtip devices to optimise drone performance and to enhance endurance will be investigated and tested extensively using CFD software in the future. The drone wing optimization will improve the drone performance by, reducing fuel consumption, larger operational range, and greater endurance.

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