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Comparison of Efficiency of Wingtip Design for Aircraft of Different Types

Weijing Liang

Oak Christian School, Thousand Oaks, US
liangconcorde@gmail.com

Abstract. Wingtip vortices are the cause of induced drag and thus reduce the efficiency of an airplane. The vortices that occur here are caused by a pressure difference on the upper and lower surfaces of the wing, thus increasing drag that can negatively affect the following aircraft and reducing the overall efficiency of the aircraft. This paper will review the development of wingtip devices, including wingtip fences, raked wingtips, canted winglets, blended winglets and split-scimitar winglets, and each design addresses the problem of induced drag in a different way. According to the results of CFD experiments and wind tunnel tests by various scholars, this paper will compare the strengths of the two devices and also discuss their structural and weight disadvantages. At the same time, experimental data can be used to improve the realism of the performance.Blended winglets and split-scimitar winglets are generally more efficient for short- and medium-range aircraft. Raked Wingtips are suitable for long-haul aircraft, however. The above differences indicate that different designs may be more suitable for various aircraft; thus, only the one with the best performance of the device needs to be selected, rather than concluding that one design is universally superior.

Keywords: Wingtip efficiency, induced drag, winglets

1. Introduction

The two reasons for this are a lower fuel cost and a need to reduce carbon emissions; thus, engineers have continuously been developing new and better designs. The first of these issues is induced drag; up to 40% of the total drag on a transport aircraft during cruise is caused by it [1].

Induced drag is the result of lift generation on a wing with a small wingspan. As the pressure difference at the lower part of the wing is relatively high compared to that at the upper part of the wing, air generally flows around the tip of the wing from bottom to top. This is a high-energy, closed loop that constitutes a wingtip vortex. These vortices cause energy loss and also create a downwash behind the wing; thus, the centre of lift moves backwards, resulting in drag and reduced efficiency [2].

Earlier, a different solution to this problem was to increase the wingspan and thus increase the aspect ratio; however, this way was limited by the constraints at the airport gate and resulted in an increase in the bending moment at the wing root. Richard Whitcomb of NASA introduced a non-planar design in the 1970s: the winglet. Place a vertical surface at the end to diffuse the vortex and

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obtain a small amount of forward thrust by recovering some energy. Whitcomb's first wind tunnel experiments found that the above surfaces could reduce induced drag by as much as 20% [3].

Whitcomb's first design has resulted in many other wingtip shapes for different flight circumstances. This paper introduces the following technologies and examines the interference drag reduction in blended winglets at the wing-junction. Further studies have explored the development of split-scimitar winglets and raked wingtips; they are designed to reduce vortex strength by employing a dual-surface structure and to increase effective span without a vertical section. Add a review of new active and morphing wingtips based on biomimicry.

2. Methods

The purpose of this paper is to systematically organise data from multiple studies on the aerodynamic and structural performance of various wingtip devices in a search of academic articles and technical papers.

The following are the academic databases and research materials used in this study: NASA Technical Reports Server (NTRS), ScienceDirect and IEEE Xplore. To cover the full development path of modern winglets and their current experimental designs, the search in publications was restricted to the period 1976-2026.3. Comparative Analysis of Wingtip Geometries

The evolution of wingtip devices has been characterized by a constant negotiation between aerodynamic efficiency and structural weight.

3. Comparison of wingtip devices

3.1. Performance of wingtip fences

Research has shown that a traditional wingtip only points upwards and, while it can stop the air at the surface of the wing from curling, it is not doing so effectively; at the same time, the air under the wing is left to move freely. Therefore, a new type of wingtip fence was developed with two parts, one pointing up and the other pointing down. The top section does not let the high-pressure air flow over the top; the bottom section also prevents side-slip of the air beneath the wing [4].

Wingtip fences are drag-inducing and result in an uneven lift distribution. A Fence design reduces the wingtip vortex more effectively than a flat wing design. It has achieved this without sacrificing stability, so it is less prone to the problem of a large wingtip. A fence can help spread out the lifting force that a wing generates more evenly.

The first of the main elements in a wingtip device is its scale. A short fence and an extended one can be Aerodynamically the same. As a result, the device is relatively small and thus light; therefore, a substantial increase in the weight of the supporting structure for this device is not required.

Wingtip fences can also increase the side load of an airplane, it has been shown. At a low speed, the wingtip fences can function as auxiliary rudders at the end of the wing to maintain level flight of the aircraft.

3.2. Classic canted winglets

It is known that a wingtip does not have to be a flat plate; instead, it should be an air foil that is curved like the real wing of a small aircraft. The air in a wingtip vortex spins both upwards and inwards, and when it reaches the vertical winglets, it does so at an angle. This is a sail boat; when the wind blows from the side, the sail is turned to create a forward-driving force. The above physics

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can also be applied to canted winglets. The canted winglets generate a side vortex and are therefore forward-thrusting. Therefore, the purpose of the winglets is to reduce induced drag for the plane, but at the same time, they can generate an additional thrust to help the wing overcome its own drag [5].

The Canting winglets are also very effective. First, the engineers proposed extending the wings to reduce induced drag, but then it was found that canted winglets were better for achieving the same goal by increasing lift. Extend the wing to reduce drag, but it will also be heavier; thus, more material needs to be added for increased strength. A vertical winglet can reduce drag to the same extent as a long horizontal wing, but is half as heavy. It is not a small, high-energy tornado; rather, it is a relatively gentle and smooth flow of air that results from the expansion of air over a large area at a vertical surface behind an aircraft.

A typical Design for canted winglets is to tilt them outwards; such canted winglets are also more efficient. When air enters at a 90° angle and connects to a winglet on the main wing, it is compressed. The speed of sound in air increases with temperature; therefore, a shockwave is generated at supersonic speeds. Increase the Angle of tilt to widen the corner. Thus, there will be no shock waves in the air. Reduce the vortex and maintain a high-speed flow of air simultaneously [6].

Canted winglets are used to reduce the vortex generated at the tip of the wing and to improve the lift of the entire wing. Generally speaking, the air moves outwards at the end of the wing. Therefore, the middle part of the wing is not effective. The winglet stops the outwards-sliding air and keeps it under the wing for a longer time. Therefore, it will raise the stress at the outer end of the wing and, as a result, increase the total lift-to-drag ratio. The plane generates a larger lift with the same amount of fuel; thus, more people can be carried or it can cover more ground.

3.3. Blended winglets

Similar to canted-winglet designs, blended winglets are relatively minor improvements rather than new ideas. Therefore, the front end of the vehicle can be rounded to reduce the aerodynamic drag of a sudden shape change. A smooth-edged blended winglet is used, and it is connected to the main wing at a small radius to avoid a visible step or joint of a traditional winglet.

The first and main difference between a conventional canted winglet and an integrated winglet is at this transition area. The corner of the old design between the wing and the winglet causes a flow separation. Air is likely to separate at this junction and thus creates a turbulent, low-energy flow that increases drag. This turbulence reduces the efficiency of the winglet and is thus unable to guide the airflow upwards smoothly.

Blended winglets are introduced to address this problem by a gradual curve. Do not force the air to change direction suddenly; instead, guide the curved surface of the wing smoothly from the wing into the winglet. Thus, attached flow is kept on the surface to reduce drag and improve the entire aerodynamic performance. Simply put, the air does not depart from the form but rather follows it.

Another advantage of a relatively smooth increase is that the performance in the transonic speed range is also high, and most commercial jet aircraft work at this speed. At this time, the speed of airflow over a part of the wing may reach or exceed the speed of sound; therefore, small shockwaves will appear. Sharp-cornered designs are more prone to generating these shock waves and thus have a larger drag. The blended shape avoids a sudden change in geometry to reduce the above effects and forms a stable-flow area [7].

Blended winglets are also suitable for this in terms of structure. The arc distributes the aerodynamic force more evenly in the vicinity of the wingtip. Sharp Corners are more likely to be areas of stress concentration at specific times and may suffer from fatigue. By spreading out these

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forces over a larger area, blended winglets reduce the risk of structural cracks and extend the service life of the wing.

In terms of efficiency, blended winglets generally have a good improvement over the previous canted designs, and fuel savings of around 1% to 5% can be achieved for certain aircraft and flight conditions. Although it appears to be a small amount, it will help commercial aviation; at a rate of 1% per year, a considerable sum of money will be saved on fuel costs [8].

Blended-winglets are generally practical in balancing the goals of improved aerodynamics and structural strength. They are not to change the function of the winglet significantly; rather, they optimize the shape and improve the behavior of airflow to enhance the design's effectiveness in modern aircraft operating environments.

3.4. Raked wingtips

As most of the wingtips shown are pointing up or down, forming a wall to reduce drag, the raked wingtip design does not have any parts that point up.

The purpose of raked wingtips is to give the impression of a longer wing than it actually is. A glider is more aerodynamic; therefore, for extended flight without engines, a high-lift, low-drag wing is required. This is referred to as a high-aspect-ratio wing, and by angling the tip backward (raking), one can increase the span of the wing. This spreads the wingtip vortex over a larger area and thus reduces induced drag to an even greater extent than a vertical winglet under certain conditions [9].

Raked wingtips are generally for very large, long-range aircraft. Raked wingtips are optimized for transonic flight at approximately 0.85 times the speed of sound for an aircraft. Vertical winglets can cause additional wave drag at high speeds. Raked tips are flat and therefore have a cleaner flow of air at high speed.

A lighter airplane is required to lift off from the ground, so less fuel will be consumed. A winglet is often a detached heavy-metal or carbon-fibre piece attached to the end of a wing; however, a raked wingtip is part of the wing and thus structurally simpler. Due to the horizontal arrangement of the weight, it cannot serve as a large lever to lift the wingtip substantially, as a high winglet would. Therefore, the wing can be built to be relatively light but still very strong.

The raked wingtips are designed to reduce induced drag in a different way as well. A raked wingtip is used to reduce the size of the vortex rather than building a wall. The back edge of a raked wingtip is relatively far from the leading edge. Therefore, the spinning air will be blown away from the wing in a very thin and flat stream. Because the vortex is thinner, there will be less hazardous wind at the back of the planes that follow it. It will be a safer sky, and the planes will be able to take off earlier.

3.5. Split-scimitar Winglet

At the bottom of a normal wing, the air is under high pressure and will try to escape sideways. The lower fin is set to be flat and does not undulate. It keeps that high-pressure air below the wing from moving up. A fin is added at the end of the wing; on this fin, one points up and the other points down to trap the air at the end. Therefore, the lift will be relatively stable, and the flow of air over the wing will not be messy or turbulent.

Since raked wingtips are more efficient for large-body, long-haul aircraft, the split scimitar winglet is more suitable for aircraft that will have many take-off and landing trips between close cities, such as a Boeing 737, a plane that is climbing will be at a high angle. Therefore, the Split-

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Scimitar will be able to reduce drag better. It has a low-drag design for climbing and, therefore, reaches the high-altitude cruising speed of the aircraft more quickly. There is less air at a higher altitude, so the engine needs to be run at a reduced speed and consume less fuel.

As the split scimitar winglet is very good in terms of flight performance, there is a mechanical trade-off of adding more weight and stress. Now that there is a bottom fin on the winglet, the wind will push on the wingtip from both sides. Thus there is a "torque" that tends to distort the wing into a wet-cloth shape. Therefore, engineers need to enter the inside of the wing to strengthen the wing spars and ribs against twisting. Therefore, they are heavy; thus, airlines will only use them for long-haul flights where the fuel savings significantly outweigh the increased weight.

Another feature of a split scimitar winglet is that it lacks a rounded tip and instead is slender and curved in a sword-like shape. The tip would be larger; thus, a small vortex can be generated spontaneously. To have a very clean separation of the air at the end, a tapered (scimitar-shaped) tip has been adopted [10]. The tall winglets may be fluttering or vibrating in the wind. The specific curved shape of the scimitar helps to keep the winglet rigid and silent, so the ride inside for the people will be smoother.

3.6. Weight penalties

All the researchers cited in this review know that adding a wingtip device increases aircraft weight. A problem in the literature is that to achieve a 1% reduction in drag, the wing spar often needs to be strengthened to bear the increased load, adding around 0.5% to the total weight of the wing [6]. This "diminishing returns" determines the break-even point of airlines for fuel savings and structural costs.

4. Discussion

Based on the five types of wingtip designs, none of them is particularly superior. Each Design is more appropriate for different circumstances. The length of the flight, size of the aircraft, speed, how frequently it takes off and lands, and so on, all affect which wingtip is better.

Wingtip design is therefore always a trade-off. Engineers need to increase the weight, cost and structural stress of better aerodynamics. A Design that is very efficient in one case may not be suitable for other cases.

4.1. Trading weight for reduced induced drag

Winglets reduce induced drag and thus save fuel. They are also relatively heavy for the aircraft. Thus, there will be a trade-off.

During a long-distance flight, the plane is at a high speed for an extended period, so the fuel saved by reducing drag generally outweighs the weight of the drag-reduction devices. But for a short-haul flight, the aircraft will be in a state of ascent and descent more frequently. Therefore, the amount of fuel saved is relatively small and may be offset by the extra weight.

There is also a structure. A Winglet is added to increase the lift of the wing at its base. This will need to reinforce the wing, and it will be heavier. Therefore, a relatively simple wingtip design or even the absence of a winglet may be more suitable for a short-haul aircraft.

4.2. Limitations of the existing computational model

A great many Wing-tip Designs have been tested in computer simulations, also known as Computational Fluid Dynamics (CFD). The above simulations are convenient, but they are not perfect.

There are relatively large disturbances in the airflow close to the wing tips. These are not easily modeled accurately, especially when the aircraft is not in a steady-state flight, such as during climbing or at a high angle of attack.

Therefore, the simulation results do not always match the actual flight data. Some of the designs, particularly new or irregular ones, may show better efficiency in simulations than in reality.

Therefore, wind tunnel tests and real-flight trials are still carried out by engineers. The results are not in agreement, so there will always be some inconsistency in the comparison of different wingtip designs.

4.3. Economic and environmental synthesis

A high cost will reduce the choice of a certain wingtip design for airlines that are limited by money. For older aircraft, winglets and other wingtip devices are often added through retrofit programs. There will be an upfront cost for the reconstruction, installation and testing of the new Design, but it will be more economical in the long run because of reduced fuel consumption and improved aerodynamics. Over time, the reduced fuel consumption will decrease expenses and thus make the retrofit of the large-aircraft fleet economically feasible.

Wingtip Design for new aircraft is usually integrated in the first round of design. Thus, the wing and its tip can be optimized as a whole and do not need to be optimized separately. As a result, the new type of airplane has a good all-around efficiency, low drag and good operating conditions.

The Design of Aircraft will be more environmentally friendly in the future. Although they have a relatively small improvement in fuel economy per flight, at a large scale, thousands of such flights will result in significant reductions in global carbon emissions and fuel consumption. Thus, the optimization of wingtips will also be concerned about costs and the environment.

Due to the above reasons, researchers are now investigating more sophisticated "active" wingtip systems. These systems are not fixed winglets or raked wingtips; instead, they can change in shape, angle or configuration during different parts of flight, such as takeoff, climb, cruise and descent. Therefore, it is expected to have a relatively good overall performance in a fixed design. However, these systems are still mainly at the experimental stage, and problems such as increased mechanical complexity, higher costs, reliability issues and maintenance requirements need to be solved before they can be widely applied in commercial aviation.

5. Conclusion

This review has presented some examples of the new integrated and more complex forms. Although all of the above new designs have reduced induced drag, their degree of reduction depends on the type of flight. Blended winglets are most suitable for narrow-body subsonic aircraft, and raked wingtips perform better in terms of range for long-haul, wide-body aircraft. Future research on morphing wingtips will aim to eliminate the trade-offs of fixed design and provide a foundation for the next generation of low-emission aircraft.

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