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Aerodynamic Analysis of Winglet Designs Using Computational Fluid Dynamics

Minxi Guo[1*], Yuqiao Zhang[1], Chengxuan Qiu[1]

[1]*Suzhou Industrial Park Xinghai Experimental Senior High School, Suzhou, China*
**Corresponding Author. Email: 2873254433@qq.com*

Abstract. In modern aviation, aircraft rely heavily on optimized aerodynamic components to maximize efficiency and performance. Winglets represent a prominent approach for reducing induced drag and improving fuel economy. This study examines the influence of key winglet design parameters—angle of attack, sweep angle, and dihedral angle (cant angle)—on overall aerodynamic performance. Using SOLIDWORKS, detailed wing and winglet models were constructed, and computational fluid dynamics simulations were performed to evaluate various parameter combinations. The results indicate that a cant angle of 30° at an angle of attack of 5° yields optimal performance, while variations in sweep angle showed negligible effects. Systematic analysis established clear relationships between these parameters and key performance metrics, including the lift coefficient (C_l) and drag coefficient (C_d). These findings offer valuable insights for the design and optimization of winglets, with promising potential to enhance the aerodynamic efficiency of future aircraft.

Keywords: Aerodynamics, Winglet design, Angle of attack, Sweep angle, Cant angle, Computational fluid dynamics

1. Introdution

In modern transportation systems, aircraft have become indispensable for long-distance travel and cargo transport due to their high efficiency and speed. Their development has profoundly reshaped global connectivity and economic exchange. The wing, as the primary lift-generating component, plays a central role in determining aerodynamic performance. Key design parameters directly influence critical flight characteristics such as efficiency, fuel consumption, and safety, making wing optimization a perennial focus of aeronautical research. As the aviation industry continues to prioritize improved fuel economy, extended range, and enhanced flight performance, refined studies on wing aerodynamics have gained increasing importance. In particular, winglets—vertical or angled extensions at the wingtip—have emerged as effective devices for reducing induced drag and improving overall aerodynamic efficiency. Parameters such as angle of attack, sweep angle, and dihedral angle (cant angle) significantly influence lift and drag coefficients, especially within complex flow environments.

Winglet design has been extensively studied for its significant aerodynamic benefits, primarily through the management of flow separation and tip vortices. Key geometric parameters—such as the angle of attack, sweep angle, and cant angle—play critical roles in optimizing performance by

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delaying stall, adapting to different flight regimes, and improving lateral stability. Computational and experimental studies have consistently validated these benefits. Takenaka et al. [1] employed CFD and wind tunnel testing to show that winglets with large cant angles reduce drag, improve fuel efficiency, and increase maximum takeoff weight. Maughmer et al. [2] found that elliptical winglets minimized induced drag in low-speed aircraft, while Merryisha and Rajendran [3] compared blended, spiroid, and sharklet designs, concluding that careful shaping and curvature are essential to avoid degrading aspect ratio performance. Zou et al. [4] introduced a decomposition-based optimization framework using surrogate models and Collaborative Optimization (CSSO) for winglet families, streamlining the design process for high-performance sailplanes. Iqbal et al. [5] tested multi-winglet configurations and observed that increasing the number of winglets (up to three) reduced the drag coefficient and increased lift across a range of incidence angles. Gavrilovic et al. [6] applied multi-objective optimization software and confirmed that induced drag increases with vortex strength at higher angles of attack, underscoring the value of wingtip devices and increased aspect ratios in drag reduction. John [7] used ANSYS Fluent with a K–ω SST turbulence model to compare winglet designs and identified a multi-tip configuration as optimal under given conditions. Azlin et al. [8] conducted 3D CFD simulations on a wing with a NACA 65-218 airfoil and winglets at various cant angles, concluding that a 45° elliptical winglet provided the highest lift-to-drag ratio.

Despite these advances, interaction effects among key parameters—such as angle of attack, sweep, and cant angle—remain inadequately explored. Changes in one parameter often produce complex cascading effects on overall aerodynamics. Although prior studies have examined individual factors, systematic analysis under multi-parameter coupling is still needed. This study aims to address this gap by investigating the effects of angle of attack, sweep angle, and cant angle on wing aerodynamic performance. Using SolidWorks for modeling and computational fluid dynamics (CFD) for simulation, we analyze how these parameters influence lift and drag coefficients. Through precise measurement and data analysis, this research seeks to clarify the relationship between wing design parameters and aerodynamic performance, contributing to the optimization of next-generation winglet designs.

2. Methodology

In this study, computational fluid dynamics (CFD) serves as the primary methodology for simulating turbulent flow around airfoils and automotive bodies. The accuracy and physical validity of these simulations rely fundamentally on the governing equations of fluid motion. The continuity equation, which enforces conservation of mass, is expressed as [9]:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

This equation ensures that mass is neither created nor destroyed within the fluid domain, requiring that the net mass flux into any control volume equals the rate of mass accumulation—a foundational constraint for physical consistency in CFD models. Complementing the continuity condition, the Navier–Stokes equations formulate the conservation of momentum. These equations implement Newton's second law in a fluid context, incorporating inertial, pressure, viscous, and external force effects. In tensor notation, the unsteady momentum equation is given by [9]:

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$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + (\nu + \nu_T)\frac{\partial^2 u_i}{\partial x_j^2} + F_i \tag{2}$$

Here, $u_i = (u, v, w)$ represents the velocity components in x, y and z directions, p is the pressure, $\nu = \mu/\rho$ is the kinematic viscosity, ν_T is the turbulent viscosity which is determined by turbulent model, ρ is the density of the air, and F_i encompasses body forces such as those imparting lift or drag on the wings. To quantify the aerodynamic performance of a wing design, the drag coefficient (C_d) and lift coefficient (C_l) are commonly employed as a key metrics. The drag coefficient provides a dimensionless measure of the vehicle's resistance to motion through a fluid, such as air. It is defined as [9]:

$$C_d = \frac{2F_D}{\rho u^2 A} \tag{3}$$

where F_D is the drag force exerted on the car, u is the freestream (streamwise) velocity, and A is the frontal area of the wing. A lower drag coefficient indicates reduced aerodynamic resistance and improved efficiency. The lift coefficient (C_l) is defined with a similar concept [9],

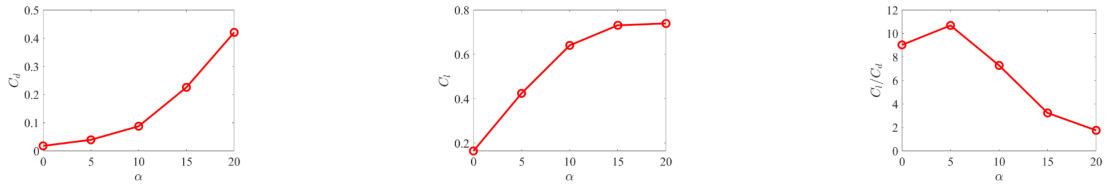
$$C_l = \frac{2F_L}{\rho u^2 A} \tag{4}$$

Here, F_L id the lift force exerted on the wing body.

3. Results and discussion

3.1. Effects of angle of attack

To establish an aerodynamic performance baseline, the optimal angle of attack (AOA) was initially investigated using a wing configuration without winglets. Simulations were conducted at AOAs of 0°, 5°, 10°, 15°, and 20° under a constant freestream velocity of 80 m/s. The wing geometry was designed to represent a typical commercial airliner wing, ensuring both practical relevance and experimental consistency.



(a) (b) (c)

Figure 1. Effect of AOA on the wing aerodynamic performance, (a) drag coefficient C_d, (b) lift coefficient C_l, and (c) lift-to-drag ratio C_l/C_d

As illustrated in Fig. 1, the angle of attack (AOA) exerted a substantial influence on all measured aerodynamic performance metrics. In Fig. 1(a), the drag coefficient (C_d) exhibits a nonlinear increase over the AOA range from 0° to 20°, indicative of rising pressure drag and progressive flow

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separation at elevated angles. Figure 1(b) demonstrates that the lift coefficient (C_l) increases almost linearly up to 10°–15° at a rate of 0.12 per degree, beyond which the rate of increase declines, signaling the onset of stall. The lift-to-drag ratio (C_l/C_d) a crucial measure of aerodynamic efficiency, attained a maximum value of 0.090 at 5° AOA (Fig. 1(c)), suggesting that moderate angles of attack optimize the trade-off between lift production and drag generation in the clean-wing configuration. These results establish an important baseline for assessing the incremental benefits of winglet integration in subsequent analyses.

Fig. 2 illustrates the flow velocity distribution around the airfoil at various angles of attack (AOA). In panel (a), at 0° AOA, the flow remains largely uniform and attached, with smooth streamlines and minimal variation in velocity, indicating stable and efficient aerodynamic behavior. Panel (b) shows that at 5° AOA, the velocity over the upper surface increases significantly, forming a pronounced high-speed region that corresponds to the initial enhancement in lift generation due to a stronger pressure gradient. At 10° AOA, depicted in panel (c), the high-velocity region on the upper surface expands further. Slight distortions in the streamlines near the trailing edge suggest early stages of flow separation, signaling a reduction in aerodynamic efficiency. Panel (d) reveals that at 15° AOA, substantial flow separation occurs on the upper surface, resulting in a disordered velocity distribution and a noticeable reduction in effective airflow velocity over parts of the airfoil. Finally, panel (e) demonstrates that at 20° AOA, the airfoil experiences deep stall, characterized by extensive flow separation, recirculation zones, and highly disrupted velocity profiles, leading to a severe degradation in performance.

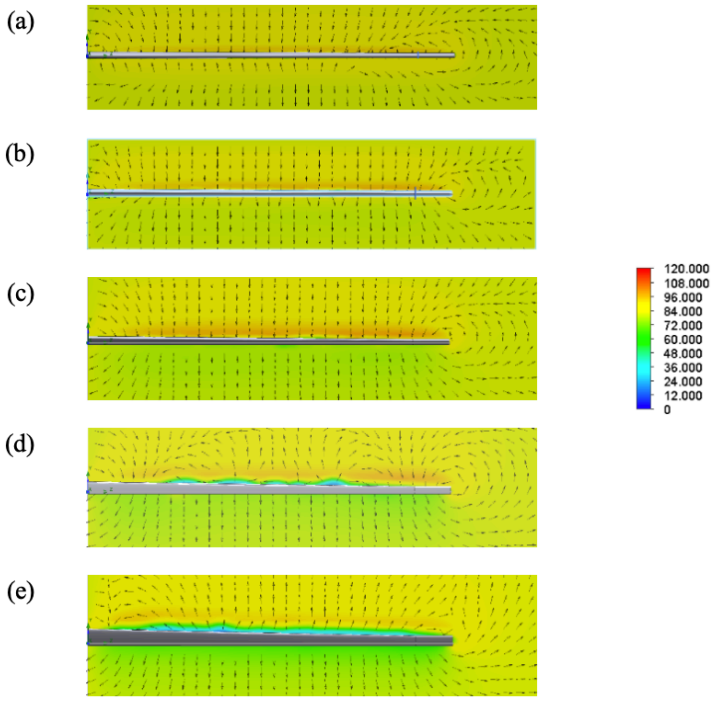


Figure 2. Pressure distribution over the airfoil at AOA of 0°, 5°, 10°, 15°, and 20°

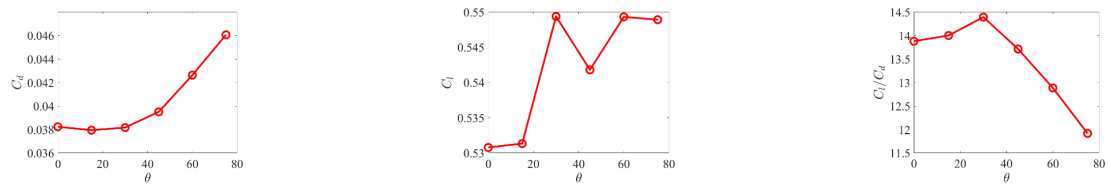
3.2. Effects of winglet cant angle

Prior research has established that wingtip vortices, resulting from the pressure differential between the upper and lower wing surfaces, diminish overall lift generation. To compensate for the

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associated downwash effect, aircraft often employ higher angles of attack, though this also increases lift-induced drag—a component of drag orthogonal to the direction of flight. Winglets have emerged as a highly effective means of reducing lift-induced drag in modern aviation. As a class of nonplanar systems, their upturned configuration improves aerodynamic efficiency by redistributing tip vortices [10]. In particular, the cant angle (θ)—defined as the inclination of the winglet relative to the vertical plane perpendicular to the aircraft's longitudinal axis—has been shown to considerably influence both aerodynamic and aeroacoustics performance [11]. To systematically evaluate this effect, we conducted a series of simulations using winglet models designed in SOLIDWORKS. The wing was based on a NACA 63-412 airfoil with a chord length of 3 m, a total wingspan of 20 m, and a winglet height of 2 m. All simulations were performed at a freestream velocity of 80 m/s and an angle of attack of 5°. Six cant angles were tested: 0°, 15°, 30°, 45°, 60°, and 75°. Lift and drag coefficients (C_l and C_d) were derived from numerical solutions of the governing flow equations, and flow velocity and static pressure fields were monitored to support physical interpretation. The lift-to-drag ratio, C_l/C_d, was used as the primary metric for evaluating aerodynamic efficiency.

Fig. 3 presents the variation of C_d and C_l as functions of the cant angle. The results indicate a clear optimal performance within the tested range, providing insight into the trade-offs involved in winglet design. Specifically, the cant angle of 30° yielded the highest lift-to-drag ratio, demonstrating a balance between lift enhancement and drag reduction. This optimal configuration effectively suppresses wingtip vortices while minimizing flow separation, contributing to improved overall aerodynamic performance.



(a) (b) (c)

Figure 3. Effect of cant angle on wing the aerodynamic performance, (a) drag coefficient C_d, (b) lift coefficient C_l, and (c) lift-to-drag ratio C_l/C_d

Fig. 4 provides a physical explanation for the improvement in the lift-to-drag ratio observed with the introduction of a winglet at an optimal cant angle. In the baseline configuration (θ = 0°), shown in Fig. 4(a), the high-speed flow over the upper surface interacts directly with the low-speed flow beneath the wing, promoting the formation of strong wingtip vortices. These vortices intensify induced drag and reduce aerodynamic efficiency. In contrast, at a cant angle of θ = 30° (Fig. 4(b)), the winglet effectively separates the high- and low-pressure regions, disrupting the spanwise flow and reducing the strength of the wingtip vortex. This mitigation of cross-flow interaction decreases the energy lost to vortex generation, thereby reducing induced drag. Simultaneously, the winglet helps maintain attached flow over the wing surface, supporting lift production. These results demonstrate that a cant angle of 30° produces the most significant enhancement in the lift-to-drag ratio. This optimum configuration effectively balances two key aerodynamic effects: the suppression of wingtip vortices to reduce induced drag and the maintenance of favorable pressure distribution to sustain lift generation. At this specific angle, the winglet guides the airflow in a manner that delays flow separation, minimizes energy loss due to vortices, and maximizes overall efficiency. In contrast, larger cant angles disrupt this balance, leading to increased drag and reduced aerodynamic stability. The winglet thus functions as an aerodynamic barrier, limiting unfavorable pressure

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equalization at the wingtip and enhancing the overall lift-to-drag ratio. The observed flow mechanisms confirm that a well-designed winglet can significantly improve performance by altering the tip vortex structure. These findings offer valuable guidance for the design and optimization of winglets, highlighting a practical approach to improving subsonic aircraft performance through carefully tailored wingtip devices.

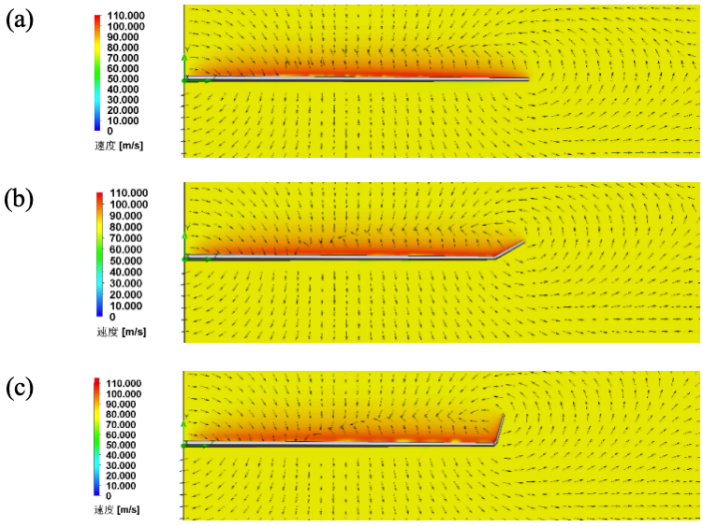
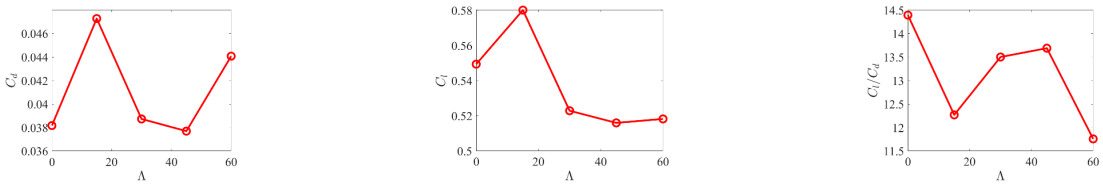


Figure 4. Velocity distribution over the airfoil at cant angles of 0°, 30°, and 75°

3.3. Effects of sweep angle

The sweep angle of a winglet, denoted as Λ, is defined as the acute angle between the winglet's leading edge and a direction normal to the aircraft's longitudinal axis. This geometric parameter influences the three-dimensional flow structure around the wingtip by altering spanwise pressure gradients and modulating crossflow velocities, which in turn affects the formation and strength of wingtip vortices [12]. To systematically evaluate the effect of sweep angle on aerodynamic performance, five winglet configurations with Λ = 0°, 15°, 30°, 45°, and 60° were designed and analyzed. The model with Λ = 0° maintained identical wing and winglet dimensions to the optimal configuration identified in Section 3.2 (θ = 30°), ensuring geometric consistency. All simulations were conducted under identical flow conditions—angle of attack of 5° and freestream velocity of 80 m/s. The lift-to-drag ratio (C_l/C_d) was computed for each sweep angle, and the results are presented in Fig. 5. The results indicate that variations in Λ produce only minor changes in aerodynamic efficiency, suggesting that sweep angle has a limited influence on performance within the tested range. This finding implies that other geometric parameters—such as cant angle—may play a more dominant role in winglet optimization for subsonic flight conditions. As shown in Fig. 5(a), the drag coefficient fluctuates around 0.043 with considerable amplitude, reaching a maximum at Λ = 15° and a minimum at Λ = 40°. Fig. 5(b) indicates that the lift coefficient also peaks at Λ = 15° but decreases sharply beyond this point, stabilizing at lower values for sweep angles exceeding Λ = 30°. Integrating these observations, Fig. 5(c) illustrates that the introduction of sweep generally reduces aerodynamic performance relative to the unswept winglet design (Λ = 0°), as reflected in the overall decline in C_l/C_d. Although a local maximum occurs at Λ = 40°, this value does not exceed the performance achieved at Λ = 0°.

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(a) (b) (c)

Figure 5. Effect of sweep angle on wing the aerodynamic performance, (a) drag coefficient C_d, (b) lift coefficient C_l, and (c) lift-to-drag ratio C_l/C_d

Fig. 6 illustrates the flow field characteristics for winglet sweep angles of Λ = 0°, 30°, and 60°. Subfigures (a) to (c) show that increasing the sweep angle does not produce visually significant changes in the global airflow structure around the wingtip. However, a more detailed analysis identifies two key mechanisms underlying the performance degradation noted earlier: First, as the sweep angle increases, the winglet's leading edge becomes less effective at redirecting the downwash flow. A portion of this flow bypasses the winglet and passes directly over the wingtip, impinging on the upper wing surface. This interaction disrupts the pressure distribution and reduces the lift generation capability of the outer wing sections. Second, the swept winglet configurations show no improvement in vortex disruption or dissipation compared to the unswept baseline. The wingtip vortices—whose suppression is a primary goal of winglet design—remain largely unaffected by changes in sweep angle. The persistence of these coherent vortical structures contributes to sustained induced drag, negating any potential benefits of sweep. Together, these effects account for the reduction in lift-to-drag ratio observed in Figure 5. The inability of swept winglets to effectively control tip vortices or maintain optimal lift distribution highlights the limited value of sweep angle as a design parameter for enhancing winglet performance in subsonic applications.

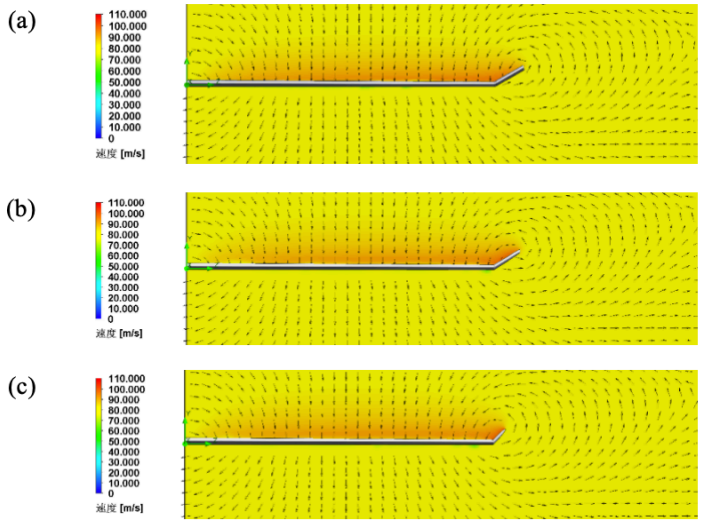


Figure 6. Velocity distribution over the airfoil at sweep angles of 0°, 30°, and 75°

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4. Conclusions

This study investigated the effects of angle of attack, cant angle, and sweep angle on the aerodynamic performance of a wing. The following conclusions were drawn from the simulation results. For Angle of Attack (AOA): As the angle of attack increases, both the lift coefficient (C_l/C_d) and drag coefficient (C_d) increase. However, larger AOAs promote stronger wingtip vortices and flow separation, reducing aerodynamic efficiency. An AOA of 5° was found to yield the optimal lift-to-drag ratio. For Cant Angle: The cant angle significantly influences aerodynamic performance. A cant angle of 30° resulted in the highest lift-to-drag ratio, minimizing induced drag while maintaining lift generation. This configuration also enhanced flight stability by reducing flow separation and vortex strength. For Sweep Angle: Variations in sweep angle (0° to 60°) had a negligible impact on aerodynamic efficiency. Swept winglet configurations did not improve vortex disruption or lift-to-drag performance compared to unswept design, indicating limited practical utility for subsonic applications. In summary, while cant angle and angle of attack play critical roles in optimizing winglet performance, sweep angle offer no discernible benefits under the conditions studied. The optimal configuration identified—a cant angle of 30° at 5° AOA—provides a balanced improvement in aerodynamic efficiency and operational stability. These findings offer practical guidance for winglet design in subsonic aviation.

Author Contribution

Minxi Guo, Yuqiao Zhang, and Chengxuan Qiu contributed equally to this work.

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