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CFD Analysis of NACA 2412 Airfoil With Winglets at Varying Cant Angles: A Comparative Study on Aerodynamic Performance

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Abstract
The integration of winglets on aircraft wings has been widely recognized as an effective method to reduce induced drag and improve overall aerodynamic efficiency. This study presents a computational fluid dynamics (CFD) analysis of a NACA 2412 airfoil wing with and without winglets at varying cant angles of 30°, 45°, and 60°. The simulations were performed using a steady-state approach under subsonic flow conditions to evaluate key aerodynamic parameters such as lift coefficient (Cl), drag coefficient (Cd), and lift-to-drag ratio (L/D). The baseline configuration without winglets served as a reference for comparison. Results indicate that the inclusion of winglets significantly reduces induced drag, with the 45° cant angle providing the most favorable balance between lift enhancement and drag reduction. Flow visualization further highlights the suppression of wingtip vortices, contributing to improved aerodynamic efficiency. These findings underscore the potential of optimized winglet designs in enhancing aircraft performance and fuel efficiency. The study provides insights for future design considerations in both commercial and unmanned aerial vehicle applications.
Keywords: *Winglets, Cant angle, Computational Fluid Dynamics (CFD), Aerodynamic performance, Lift-to-drag ratio (L/D).*

1. Introduction
The aerodynamic efficiency of aircraft wings plays a crucial role in reducing fuel consumption and enhancing overall performance. One widely adopted technique to improve aerodynamic characteristics is the integration of winglets at the wingtips. Winglets are small, upward or outward extensions designed to minimize induced drag caused by wingtip vortices, thereby improving lift-to-drag ratio (L/D) and fuel efficiency (Whitcomb, 1976; Kroo, 2001). The concept has been extensively applied in both commercial and unmanned aerial vehicles, offering benefits such as reduced vortex strength, improved climb performance, and extended range (Nikolaou, E et al., 2025). The NACA 2412 airfoil, a commonly used cambered airfoil in general aviation, provides a suitable baseline for studying the effects of winglet configurations. Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analyzing aerodynamic performance under various conditions, enabling detailed visualization of flow patterns and accurate prediction of aerodynamic coefficients (Anderson, 2010; Versteeg & Malalasekera, 2007). Previous studies have demonstrated that winglet geometry, including cant angle, sweep, and toe angle, significantly influences aerodynamic behavior (Babu, D. et.al, 2025; Nakka, M et al., 2025). This research focuses on the comparative analysis of NACA 2412 airfoil with winglets at varying cant angles—30°, 45°, and 60°—under subsonic flow conditions. The objective is to evaluate how cant angle affects key aerodynamic parameters such as coefficient of lift (Cl), coefficient of drag (Cd), and lift-to-drag ratio (L/D). By employing CFD simulations, this study aims to provide insights into optimal winglet configurations for improved aerodynamic efficiency, contributing to future design considerations in both conventional and UAV applications.

2. Methodology
2.1. Geometry and Winglet Configuration
Three CAD models of the NACA 2412 airfoil were developed, each incorporating winglets with cant angles of 30°, 45°, and 60°. These configurations were designed to analyze the effect of cant angle on

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aerodynamic performance under subsonic flow conditions (Figure 1). A structured mesh was generated around the airfoil-winglet assembly to ensure accurate resolution of boundary layer effects and flow separation regions. Mesh refinement was applied near the airfoil surface and winglet junction to capture critical flow features. The computational domain and applied boundary conditions are shown in The simulations were performed under steady-state conditions using the k-ω SST turbulence model. The following boundary conditions were applied: Inlet: Uniform velocity of 30 m/s, Outlet: Pressure outlet condition, and Walls: No-slip condition on the airfoil and winglet surfaces.

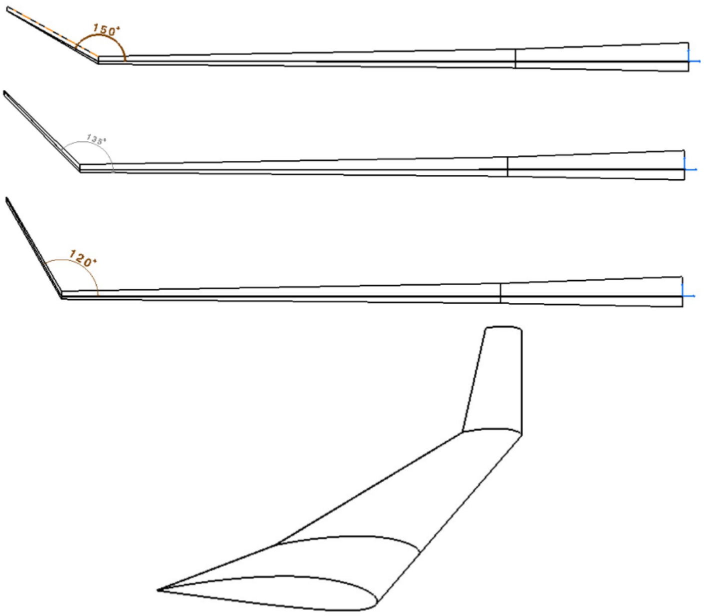

Figure 1. CAD Models of NACA 2412 Airfoil with Winglets at Cant Angles of 30°, 45°, and 60°

3. Results and Discussion

The CFD simulations were conducted for the NACA 2412 airfoil with winglets at cant angles of 30°, 45°, and 60° under subsonic flow conditions at an inlet velocity of 30 m/s. The results were analyzed in terms of Coefficient of Lift (Cl), Coefficient of Drag (Cd), and Lift-to-Drag Ratio (Cl/Cd) across angles of attack ranging from 0° to 18°.

3.1. Discussion

Figure 2 illustrates the variation of Cl with AoA for all three winglet configurations. It is observed that Cl increases almost linearly with AoA for all cases, with the 60° cant angle showing slightly higher lift at higher AoA compared to 30° and 45°. Figure 3 shows the variation of Cl/Cd with AoA, indicating that aerodynamic efficiency decreases as AoA increases due to the rapid rise in drag. At low AoA (0°–6°), the 45° winglet configuration provides the highest Cl/Cd ratio, suggesting optimal performance in cruise conditions.

3.2. Flow Visualization

Velocity contours and streamline plots (Figures 4 and 5) confirm the reduction in wingtip vortices for winglet-equipped configurations compared to the baseline. Among the three, the 45° cant angle demonstrates effective vortex suppression without introducing excessive interference drag.

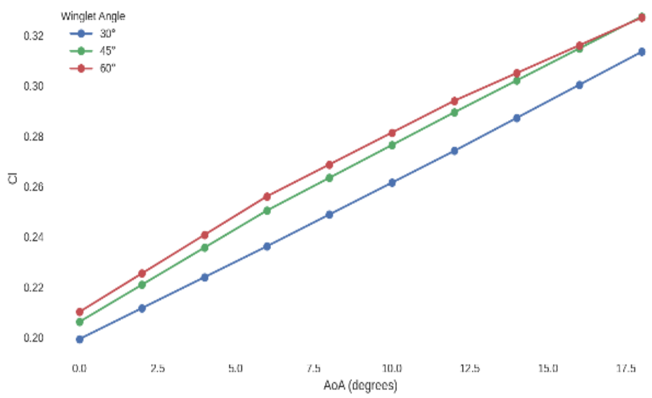

Figure 2 Variation of Cl with AoA for Winglet Cant Angles Of 30°, 45°, and 60°

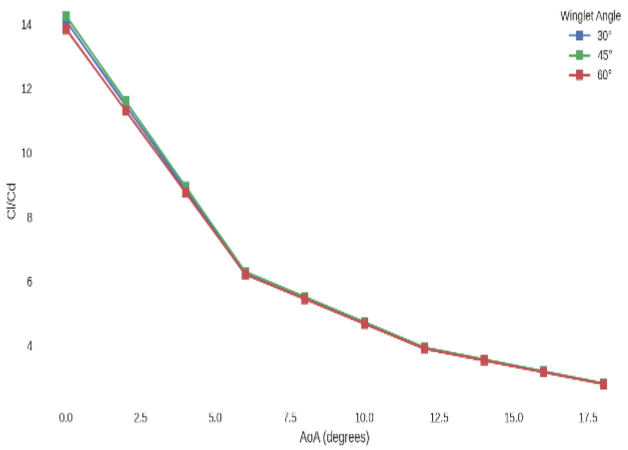

Figure 3. Variation of Cl/Cd with AoA for Winglet Cant Angles of 30°, 45°, and 60°

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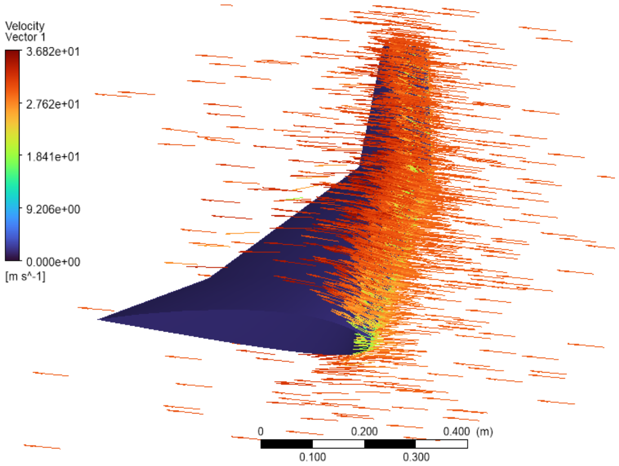

Figure 4. **Velocity Vector Contour Plot Showing Flow Behavior Around the Winglet at 45° Cant Angle**

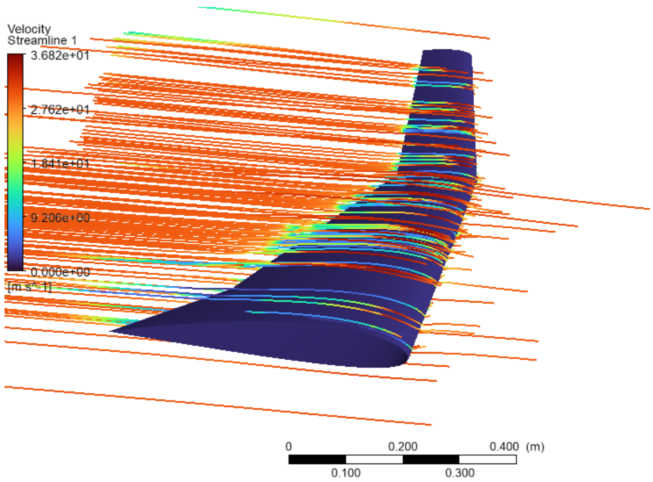

Figure 5. **Streamline Visualization Highlighting Vortex Reduction for Winglet-Equipped Configurations**

Conclusion

This study investigated the aerodynamic performance of a NACA 2412 airfoil equipped with winglets at varying cant angles of 30°, 45°, and 60° using Computational Fluid Dynamics (CFD) under subsonic flow conditions. The results demonstrated that the integration of winglets significantly reduces induced drag and improves overall aerodynamic efficiency compared to the baseline configuration. Among the three configurations, the 45° cant angle provided the most favorable balance between lift enhancement and drag reduction, achieving the highest lift-to-drag ratio (Cl/Cd) at lower angles of attack. The 60° cant angle exhibited slightly higher lift at higher AoA, but with a marginal increase in drag. Flow visualization confirmed that winglets effectively suppress wingtip vortices, contributing to improved aerodynamic performance. These findings highlight the importance of winglet geometry in optimizing aircraft efficiency. The insights gained from this study can guide future design considerations for both conventional aircraft and unmanned aerial vehicles, where improved fuel economy and extended range are critical.

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