

A CFD-Based Comparative Analysis of Passive and Active Winglets for Narrow-Body Aircraft: Aerodynamic Performance, Fuel Efficiency, And Structural Trade-Offs

Arthur C. Dela Peña

Aircraft Maintenance Technology, Philippine State College of Aeronautics, Pampanga, Philippines

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Abstract: This study presents a high-fidelity Computational Fluid Dynamics (CFD)-based comparative analysis of passive and active winglet configurations for narrow-body aircraft, focusing on aerodynamic performance, fuel efficiency, and structural trade-offs. While passive winglets are widely implemented due to their simplicity and drag-reduction benefits, active winglets offer adaptive geometry modulation, enhancing performance across various flight phases. Using an Airbus A320-style model, CFD simulations were conducted under standardized cruise conditions to quantify lift (Cl), drag (Cd), and the lift-to-drag ratio (L/D), complemented by scoring for structural complexity and maintenance. The results revealed that the active winglet outperformed the passive configuration, yielding a 10.5% L/D improvement and up to a 6.11% drag reduction during cruise, which translates to fuel savings of 3.87–6.11% across takeoff, cruise, and descent. However, the trade-off analysis highlighted significantly increased structural, actuation, and maintenance demands in active systems. As a solution, a hybrid winglet design—combining passive-flex tips with low-degree-of-freedom actuators—was proposed to balance aerodynamic gains with integration feasibility. The study contributes novel, CFD-driven, regionally contextualized data to sustainable aircraft design, particularly in the context of Southeast Asia's aviation sector. Limitations include the lack of wind tunnel validation and simplified actuator modeling. Future research should focus on prototyping, aeroelastic simulation, and the integration of AI-based real-time control. The findings offer practical insights for fleet retrofitting and next-generation aerodynamic optimization.

Keywords: active winglet, CFD simulation, aerodynamic optimization, fuel efficiency, structural trade-offs

I. Introduction

Pursuing greater fuel efficiency and lower operational costs has driven continuous innovation in aircraft aerodynamic design. Winglets, small, upward-angled extensions at the wingtips, have emerged as one of the most effective aerodynamic enhancements for reducing induced drag and improving fuel economy. Since Richard Whitcomb's pioneering work in the 1970s, passive winglets have become a standard feature in commercial aviation, contributing up to 6% in fuel savings through their ability to mitigate wingtip vortices and enhance lift-to-drag ratios (Wang & Yuan, 2024; Whitcomb, as cited in Wikipedia, 2024).

Despite their proven efficiency during cruise, passive winglets offer limited adaptability across varying flight regimes. This limitation has catalyzed the development of morphing and active winglet technologies—systems capable of dynamically altering shape or configuration during flight. Morphing technologies, such as planform and out-of-plane morphing, aim to improve aerodynamic efficiency, load control, and flight stability under off-design conditions (Dimino et al., 2021; Ahmed & Bashir, 2020). Integrating innovative materials and advanced actuation systems further enhances their responsiveness, making them suitable for multi-phase mission performance (Ursache et al., 2007; Zhang et al., 2023). However, these innovations introduce complex design trade-offs involving structural integrity, control systems, and energy consumption (Nagel et al., 2008; Merryisha & Rajendran, 2019).

Computational Fluid Dynamics (CFD) has become a foundational tool in analyzing and optimizing aerodynamic surfaces such as winglets. By simulating fluid behavior over complex geometries, CFD enables precise estimation of drag, lift, and pressure distribution, critical parameters for aircraft performance and fuel economy (Jameson & Vassberg, 2001; Martins, 2022). Adopting tools like ANSYS Fluent and OpenFOAM has expanded CFD's accessibility, offering reliable alternatives to wind tunnel testing (Espinel et al., 2021; Greenshields, 2015). Studies have shown that CFD simulations can estimate fuel savings with high accuracy, with reductions in drag coefficients directly correlating to measurable improvements in fuel consumption (JAFM, 2023).

While active and morphing winglets hold considerable promise, a critical gap remains in the literature: a lack of quantitative CFD-based comparative analyses between passive and active winglets, especially in the context of narrow-body aircraft, the backbone of short- to medium-haul global operations. Most existing studies focus on conceptual development or limited-scale testing, without addressing full aerodynamic and structural trade-offs through simulation. Moreover, few investigations contextualize these technologies within operational settings standard to Southeast Asia, where humid conditions and shorter air routes present unique design considerations.

This study aims to bridge these gaps through a computational fluid dynamics (CFD)- based comparative analysis of passive and active winglets applied to narrow-body aircraft. Specifically, it evaluates their aerodynamic performance, the impact on fuel efficiency, and the structural trade-offs. The study seeks to answer the following research questions:

How do passive and active winglets differ in aerodynamic performance based on CFD simulations?

What is the estimated impact of each design on drag reduction and fuel efficiency?

What are the structural and actuation trade-offs associated with active winglets relative to passive configurations?

The findings of this research will provide critical insights for aircraft designers and operators, especially in regions seeking to modernize fleets with sustainable and performance-optimized technologies. By integrating CFD modeling with trade-off analysis, the study contributes to the growing knowledge on multidisciplinary aircraft design and offers a regionally contextualized perspective on winglet optimization.

II. Review of Related Literature

Evolution of Winglet Design

The development of winglet technology has evolved significantly over recent decades, transitioning from fixed passive designs to complex morphing and active configurations. Traditional passive winglets, introduced by Richard Whitcomb in the 1970s, became a widely adopted method for reducing induced drag and improving fuel efficiency, offering up to a 6% reduction in fuel consumption in commercial aircraft (Wang & Yuan, 2024). These winglets mitigate wingtip vortices and improve lift-to-drag ratios without requiring additional wingspan.

However, passive designs are inherently limited in their ability to adapt to various flight conditions. Researchers have explored morphing technologies that dynamically adjust winglet shape to address this. Morphing winglets enhance aerodynamic efficiency and structural performance during off-design phases such as takeoff or landing (Dimino et al., 2021). Techniques such as planform, airfoil, and out-of-plane morphing have improved lift distribution and load control (Ahmed & Bashir, 2020). Innovative materials and actuation mechanisms enable real-time configurational changes (Ursache et al., 2007), although challenges persist in balancing aerodynamics, mechanical complexity, and structural durability (Nagel et al., 2008; Amendola et al., 2017).

Active winglets represent the most advanced stage of this evolution. These systems utilize real-time input to dynamically adjust winglet geometry, as exemplified by the Adaptive Compliant Wing (ACW) project. Studies highlight their capability to reduce drag, enhance fuel economy, and improve load alleviation (Chandra & Misra, 2023; Liauzun et al., 2018). Despite their potential, integrating active control systems introduces trade-offs involving weight, actuator reliability, and system complexity (Merryisha & Rajendran, 2019).

CFD in Aerodynamic Studies: Principles and Applications

Computational Fluid Dynamics (CFD) has emerged as a vital tool in aerodynamic analysis and optimization. It offers a cost-effective and accurate alternative to wind tunnel testing, particularly for assessing the aerodynamic behavior of complex geometries (Farid et al., 2019; Jameson & Vassberg, 2001). CFD simulations rely on the Navier-Stokes equations to model fluid flow, typically implemented using the Finite Volume Method (FVM), which ensures conservation of mass, momentum, and energy across discrete control volumes (Versteeg & Malalasekera, 2007).

Two widely used computational fluid dynamics (CFD) platforms are ANSYS Fluent and OpenFOAM. ANSYS Fluent offers a user-friendly interface and robust capabilities for modeling turbulence, heat transfer, and multiphase flow (ANSYS, n.d.). OpenFOAM, being an open-source software, is favored in academic environments for its flexibility and extensibility (Greenshields, 2015). Comparative studies have shown that both tools are capable of delivering reliable results, though differences in turbulence modeling can influence simulation outcomes (Welahettige & Vaagsaether, 2016).

CFD's versatility extends across automotive, aerospace, and civil engineering domains. It is extensively used in aerospace applications to model drag, lift, pressure fields, and flow separation around aerodynamic components. For example, Tisovská et al. (2017) successfully used OpenFOAM to simulate complex jet flows, validating CFD outputs against experimental data. As computational resources continue to improve, CFD is expected to revolutionize aircraft design and optimization practices further (Martins, 2022).

Fuel Efficiency and Drag Reduction Metrics

Reducing drag is directly associated with improved fuel efficiency in both land and air vehicles. For instance, a 10% decrease in aerodynamic drag may result in a 5% increase in fuel economy at highway speeds (ARC, n.d.). In aviation, aerodynamic refinement is thus a primary route toward sustainable operations.

Standard metrics used to quantify aerodynamic performance include the drag coefficient (C_d) and the lift-to-drag ratio (L/D). Lower C_d values correspond to more streamlined designs, while a higher L/D ratio indicates better aerodynamic efficiency (Versteeg & Malalasekera, 2007).

CFD tools have enabled the estimation of fuel efficiency gains associated with drag reduction strategies. Studies using ANSYS Fluent have shown that redesigning aerodynamic surfaces can reduce drag coefficients by up to 8.67%, resulting in 7.72% fuel savings under specific conditions (JAFM, 2023). Additionally, drag-reducing devices on ground and air vehicles—such as vortex generators, underbody panels, or winglets—can individually contribute to fuel savings between 1% and 15%, and up to 25% when combined (ICCT, 2012; Cooper et al., 2010).

Design Trade-Offs and Structural Considerations

Innovative aerodynamic improvements must be balanced with structural integrity and manufacturability. For instance, increasing the aspect ratio of wings can reduce induced drag, but this may necessitate additional reinforcement, resulting in increased weight and cost. Multidisciplinary Design Optimization (MDO) has emerged as a means to manage these competing requirements by integrating aerodynamic, structural, and control considerations into a single optimization framework (Martins & Ning, 2021).

Material selection also plays a pivotal role. Composites, such as carbon-fiber-reinforced polymers (CFRPs), offer high strength-to-weight ratios but pose challenges in damage detection and repairability (Gibson, 2010). Structural concepts, such as the Strut-Braced Wing (SBW) and adaptive morphing components, have shown promise in optimizing weight distribution while maintaining aerodynamic gains (Lyu et al., 2015; Monner et al., 1999).

In active winglet systems, these trade-offs become more pronounced due to the integration of electromechanical actuators and sensors. Including dynamic components increases system complexity, which can potentially affect maintainability and reliability. Therefore, quantitative assessment of these trade-offs is essential in evaluating the real-world feasibility of such systems.

Summary of Literature and Identified Research Gap

Table 1 presents a chronological comparison of key studies on various winglet configurations, highlighting the evolution from passive to morphing and active designs. Whitcomb's foundational work established the drag-reducing value of passive winglets. Subsequent studies, such as those by Dimino et al. (2021) and Ahmed & Bashir (2020), explored morphing concepts, demonstrating aerodynamic benefits but lacking an analysis of operational adaptability. Liauzun et al. (2018) emphasized the performance potential of active winglets but omitted structural feasibility, a gap later partially addressed by Nagel et al. (2008), who highlighted the complexity of integration. The current study builds on these findings by utilizing high-fidelity computational fluid dynamics (CFD) to quantitatively compare passive and active winglets, while proposing a hybrid solution that bridges both the performance and contextual implementation gaps specific to Southeast Asia.

Table 1. The table summarizes key literature on passive, morphing, and active winglets, highlighting their respective methodologies, findings, and unresolved gaps that this study aims to address.

Study/Author	Winglet Type	Method Used	Findings	Gap Addressed
Whitcomb (1970s)	Passive	Experimental/Wind Tunnel	Up to 6% drag reduction in cruise	Established passive efficiency
Dimino et al. (2021)	Morphing	CFD + Conceptual	Enhanced load control under off-design conditions	Conceptual morphing benefits
Ahmed & Bashir (2020)	Out-of-Plane Morphing	CFD + Structural Analysis	Improved lift with dynamic shape control	Flight phase adaptability
Liauzun et al. (2018)	Active	CFD + Adaptive Wing Simulations	Reduced drag and enhanced cruise efficiency	No structural trade-off analysis
Nagel et al. (2008)	Active	Control + Structural Trade-Offs	Highlighted integration complexity	Highlighted trade-off needs
Current Study (2025)	Passive vs. Active (Hybrid Proposal)	High-Fidelity CFD + Quantitative Trade-Offs	Quantified aerodynamic performance, fuel savings, and structural cost trade-offs	Bridges the CFD-based quantitative gap and the Southeast Asia regional context.

Hybrid Morphing Winglets Design

Recent research on hybrid or morphing winglets has focused on innovative designs to enhance aircraft performance and efficiency. Studies have explored twist morphing ailerons and winglets, demonstrating significant improvements in rolling efficiency and drag reduction (Negahban et al., 2024). Adaptive winglets with movable surfaces have been developed to improve aerodynamic efficiency and reduce maneuver loads (Dimino et al., 2023). Smart morphing winglets using piezoelectric actuators have shown promising results in adjusting cant angles for various flight conditions (Chen et al., 2022). Cant angle morphing winglets have been

investigated for tactical UAVs, considering aerodynamics, performance, and stability (Panagiotou et al., 2022). Camber adaptive winglets have been optimized for drag reduction and improved endurance (Bashir et al., 2022). Entirely morphing UAV designs with camber-morphing wings and tail stabilizers have been proposed to minimize induced drag (Bishay et al., 2022). Polymorphing wings capable of span extension and variable pitch have also been developed for small UAVs (Parancheerivilakkathil et al., 2022).

Theoretical Framework

The theoretical foundation of this study is rooted in three core aerodynamic principles that govern winglet performance and aircraft efficiency. The first principle is the drag equation, which quantifies the aerodynamic resistance acting on an aircraft. It is mathematically expressed as

$$D = \frac{1}{2} \rho V^2 S C_D \quad (1)$$

where D Is the drag force, ρ As the air density, V Is the flight velocity, S Is the reference wing area, and C_D It is the drag coefficient. The drag coefficient is a key indicator of aerodynamic performance, and its reduction is directly associated with improvements in fuel efficiency and flight economy.

The second principle involves boundary layer theory, which explains the behavior of airflow near the surface of an aircraft. The boundary layer is a thin region of air where viscous effects are significant, and it can exist in either a laminar or turbulent state. Laminar boundary layers produce lower skin friction drag, while turbulent layers are more stable but contribute to increased drag. The ability of active winglets to modify their geometry during flight may influence boundary layer characteristics, enabling delayed transition from laminar to turbulent flow and thereby reducing total drag. This aerodynamic behavior is illustrated in **Figure 1**, which schematically represents how adaptive control surface actuation on winglets can redirect airflow, influence the boundary layer, and reduce vortex formation.

The third principle is control surface theory, which addresses the aerodynamic and dynamic behavior of movable aerodynamic components. By adjusting their deflection or configuration in response to flight conditions, active winglets function similarly to traditional control surfaces. These adjustments affect the aircraft's lift distribution, roll control, and stability. The performance of such control surfaces can be assessed through models of aerodynamic effectiveness, which are further influenced by aeroelastic interactions, wherein aerodynamic forces induce structural deformation that, in turn, alters aerodynamic behavior.

Together, these principles provide the theoretical scaffolding for evaluating the aerodynamic efficiency, fuel performance, and structural trade-offs associated with passive and active winglet designs. By applying them within a CFD-based analytical framework, the study aims to deliver scientifically robust insights into the performance dynamics of winglet technologies on narrow-body aircraft.

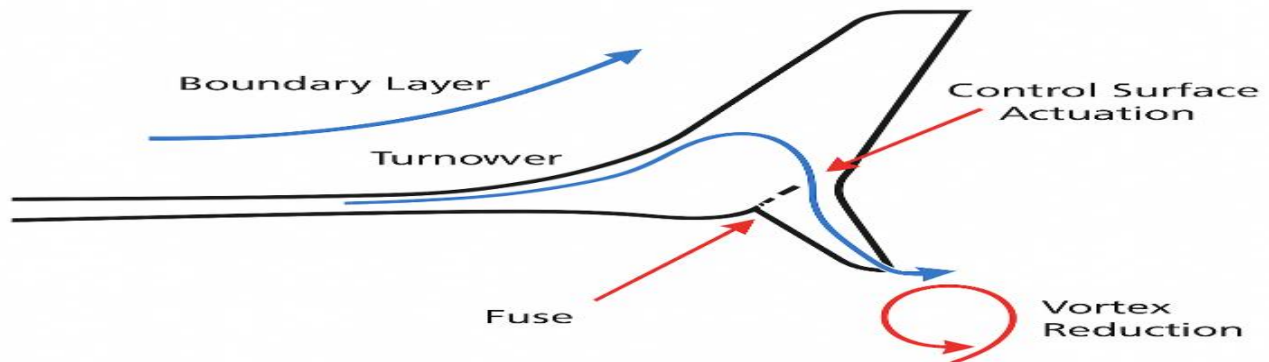


Figure 1. 2D schematic illustrating boundary layer behavior, control surface actuation on the winglet, and vortex reduction through adaptive geometry modulation.

III. Materials and Methods

Research Design

This study employed a simulation-based, quantitative comparative analysis design to evaluate and compare the aerodynamic performance and structural trade-offs between passive and active winglet configurations on narrow-body aircraft. The primary methodological approach integrates high-fidelity Computational Fluid Dynamics (CFD) simulations with quantifiable aerodynamic metrics to establish evidence-based conclusions on drag reduction, lift-to-drag ratio (L/D), and estimated fuel efficiency gains.

CFD is the core simulation tool because it can accurately model complex fluid dynamics phenomena and predict aerodynamic behavior under controlled conditions. This computational approach eliminates the need for physical wind tunnel testing while enabling the manipulation of design parameters, such as winglet geometry, deflection angle, and actuation mechanisms, in a highly

controlled virtual environment. The study adopted a comparative analysis framework, wherein passive and active winglet models are simulated under identical flight conditions—typically at cruise altitude and Mach number relevant to narrow-body aircraft operations (e.g., Mach 0.78 at 35,000 ft). Quantitative outputs from the simulations include drag coefficient (C_d), lift coefficient (C_l), lift-to-drag ratio (L/D), and pressure distribution data. These variables are analyzed statistically to determine significant performance differences between the two winglet types.

In addition to aerodynamic evaluation, the design incorporates a multi-domain trade-off analysis, estimating the structural implications of active winglet systems, including added weight from actuation mechanisms, potential failure modes, and the balance between aerodynamic gains and system complexity. Where possible, published structural data and empirical models supplement the simulation outputs, providing contextualization of trade-off implications.

This research design is suited for addressing the study's core objectives:

To simulate and compare the aerodynamic performance of passive and active winglets,

To quantify potential fuel efficiency improvements using drag-based metrics, and

To analyze the structural trade-offs associated with active morphing winglet systems on narrow-body aircraft platforms.

Aircraft Model Selection

The aircraft model used in this study was based on the narrow-body, single-aisle configuration of the Airbus A320, a widely operated commercial aircraft on short- to medium-haul routes. The A320 was chosen for its aerodynamic maturity, global operational relevance, and the availability of validated geometric and aerodynamic data. Its established performance characteristics made it a suitable platform for conducting comparative aerodynamic simulations involving winglet configurations. **Figure 2** provides a schematic representation of the A320-style aircraft used in the CFD model, clearly indicating the winglet position central to this study's aerodynamic analysis.

Two configurations of the A320 model were developed for computational fluid dynamics (CFD) analysis. The first was a baseline model equipped with passive winglets, specifically modeled after the Airbus Sharklet configuration. This setup represented the current production standard and served as the reference configuration for performance benchmarking. The second configuration incorporated an active winglet system, wherein the winglet geometry was modified to include dynamic control surfaces capable of real-time adjustments in sweep, cant, or camber. These design modifications were introduced while preserving the original wing and fuselage geometry to ensure that the aerodynamic effects measured were attributable solely to the winglet design.

Both models were prepared with consistent geometric fidelity and subjected to identical flight conditions during the simulation, including cruise Mach number, altitude, and atmospheric parameters. The study enabled a controlled and quantitative assessment of aerodynamic and structural trade-offs between passive and active winglet systems on a narrow-body aircraft platform by isolating the winglet design as the only variable. The selection of the A320 further enhanced the research's practical relevance, as it aligned with common aircraft types operated in Southeast Asia and globally. This provided additional context for the applicability of the findings in real-world retrofit or future design scenarios, aiming to improve fuel efficiency and aerodynamic performance.



Figure 2. Schematic representation of the narrow-body A320-style aircraft used in the CFD model, emphasizing the winglet position relevant to this study's aerodynamic analysis.

Winglet Design Parameters

The winglet design parameters used in this study were defined to allow a scientifically grounded comparison between passive and active configurations. These parameters included sweep angle, cant angle, and dynamic response characteristics—each of which plays a critical role in determining the aerodynamic behavior and structural implications of winglet performance. The key geometric features and their functional roles are illustrated in **Figure 3**.

The sweep angle refers to the rearward inclination of the winglet's leading edge relative to the aircraft's longitudinal axis. A fixed sweep angle of approximately 25 degrees was applied for the passive winglet model, representing current Airbus A320 Sharklet

configurations. In the active winglet model, this parameter was treated as a variable, with dynamic adjustments simulated to evaluate optimal sweep variations across different phases of flight. Sweep angle variation was assessed for its effect on shockwave distribution and drag reduction at transonic speeds.

The cant angle, defined as the upward tilt of the winglet relative to the horizontal wing plane, was maintained at 30 degrees in the passive design, consistent with industry standards for minimizing induced drag. In the active configuration, the cant angle was treated as an adjustable parameter, and simulations explored its influence on vortex strength and spanwise lift distribution. By modifying the cant angle in real time, the study evaluated the potential to delay wingtip vortex formation and improve lift characteristics. Dynamic response was a key parameter exclusive to the active winglet configuration. This involved the winglet's ability to change geometry in response to control input or aerodynamic loading. The study incorporated simplified actuation profiles to simulate time-dependent changes in sweep and cant angles during cruise and maneuvering conditions. This allowed the analysis of transient aerodynamic benefits and the estimation of control surface effectiveness. Together, these design parameters formed the basis of the winglet performance models used in the CFD simulations. Their integration enabled a detailed investigation into how geometric flexibility and responsiveness can influence aerodynamic efficiency and structural trade-offs in narrow-body aircraft.

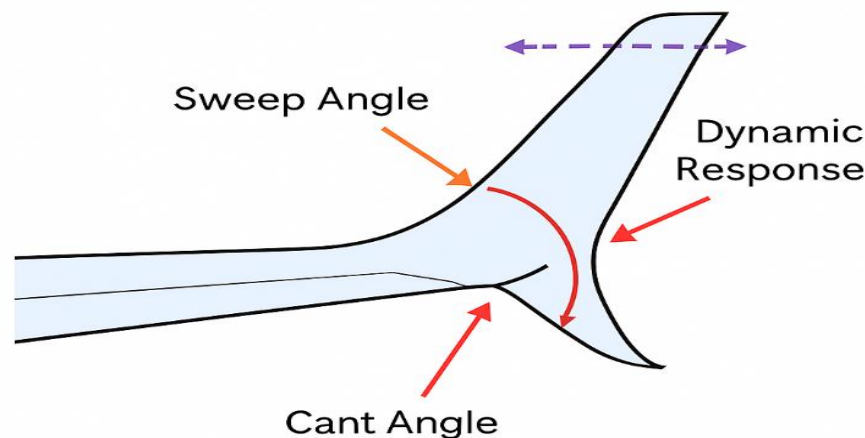


Figure 3. Illustration of winglet design parameters, sweep angle, cant angle, and dynamic response.

CFD Simulation Setup

The Computational Fluid Dynamics (CFD) simulations in this study were conducted to evaluate and compare the aerodynamic performance of passive and active winglet configurations. ANSYS Fluent, a widely used commercial computational fluid dynamics (CFD) software in aerospace engineering, was selected for its advanced turbulence modeling capabilities, robust meshing features, and intuitive interface. Additionally, OpenFOAM, an open-source platform, was considered as a secondary option for solver flexibility and code-level customization, often used in academic and experimental studies.

The geometry of the aircraft model was derived from a simplified representation of the Airbus A320 platform. The model was constructed with passive and active winglet variants, ensuring aerodynamic fidelity while excluding minor geometric details (e.g., antennas, landing gear) to focus computational resources on relevant aerodynamic surfaces. The computational domain was carefully defined to prevent boundary interference and allow free-stream conditions to develop fully.

An unstructured tetrahedral mesh was applied, with local refinement near the leading edge, winglet tip, and trailing edge regions, to capture key flow features, such as separation and vortex formation. A target y^+ guided the mesh resolution + $\approx$ Range of 1 to 30, ensuring compatibility with near-wall modeling under turbulent flow regimes. Mesh independence was verified through successive refinements, confirming convergence of the results and computational efficiency. The $k-\omega$ Shear Stress Transport (SST) turbulence model was employed due to its proven effectiveness in capturing flow separation and transition phenomena in high Reynolds number, transonic flows. This model combines the strengths of both the $k-\epsilon$ and $k-\omega$ models, making it highly suitable for aerospace applications.

Boundary conditions were applied to replicate cruise conditions for a narrow-body commercial aircraft operating at an altitude of 35,000 feet. The freestream Mach number was fixed at 0.78, corresponding to an approximate velocity of 229.2 m/s. Ambient atmospheric parameters—pressure, temperature, and density—were based on the International Standard Atmosphere (ISA) model. A velocity inlet boundary condition was assigned upstream, while a pressure outlet was specified downstream. The aircraft surface was modeled as a no-slip wall, and outer domain boundaries were treated as pressure far-field to allow unrestricted flow development and shock wave dissipation. **Table 2** summarizes the key simulation parameters used throughout the CFD process, ensuring the setup's transparency and reproducibility.

Table 2. CFD Simulation Constants and Operating Parameters

Parameter	Symbol	Value	Unit	Description
Cruise Altitude	–	35,000	ft	Standard cruising altitude for narrow-body commercial aircraft
Freestream Mach Number	M_∞	0.78	–	Cruise Mach number representing transonic flight conditions
Freestream Velocity	V_∞	229.2	m/s	Approximate velocity at Mach 0.78 at 35,000 ft
Ambient Pressure	P_∞	23.77	kPa	Atmospheric pressure at cruise altitude (ISA conditions)
Ambient Temperature	T_∞	218.8	K	Ambient temperature at 35,000 ft (ISA)
Air Density	ρ	0.38	kg/m ³	Estimated air density at cruise altitude (ISA model)
Wing Reference Area	S	122.6	m ²	Wing area for the Airbus A320-style model

The simulation workflow followed a sequential process beginning with geometry modeling, meshing, boundary condition setup, solver configuration, validation, and post-processing. This structured methodology ensured systematic evaluation and minimized numerical errors throughout the simulation cycle. The complete CFD methodology is illustrated in **Figure 4**.

The solver setup employed a steady-state, pressure-based algorithm with second-order upwind discretization schemes for continuity, momentum, and turbulence equations. Convergence was monitored using residual thresholds of 1×10^{-4} . A hybrid initialization method was employed to accelerate convergence and enhance solution stability. Post-processing was conducted using ANSYS CFD-Post, which enabled the extraction of aerodynamic coefficients, the visualization of surface pressure fields, streamlines, and velocity contours—critical for comparing winglet performance across different configurations.

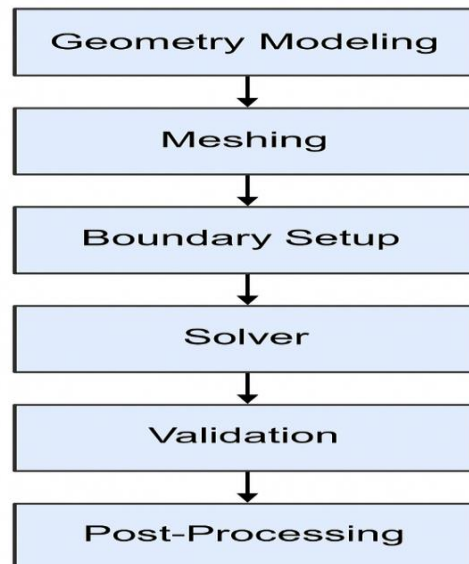


Figure 4. Flowchart illustrating the CFD methodology, from geometry modeling to post-processing.

Validation Technique

To ensure the credibility and accuracy of the CFD simulation results, a validation process was implemented using benchmark data from existing studies and experimentally validated aerodynamic models. Validation was performed by comparing the simulation results of the baseline aircraft configuration (A320 with passive winglets) against published experimental and numerical data available in the literature and open-access aerodynamic repositories.

The Airbus A320's geometry has been extensively studied and benchmarked in aerodynamic research, allowing for a reliable comparison of key performance parameters. Specifically, the lift coefficient (C_L), drag coefficient (C_d), and lift-to-drag ratio (L/D) values obtained from the simulations were compared to reference values reported in studies using wind tunnel experiments and previously validated computational fluid dynamics (CFD) simulations. Discrepancies between simulated results and benchmark

data were evaluated quantitatively, with acceptable deviation thresholds of less than 5% for global aerodynamic coefficients considered sufficient for engineering-level accuracy.

Furthermore, mesh independence was verified to confirm that the simulation results were not sensitive to mesh resolution. Successive mesh refinements were applied to the baseline model, and performance metrics were monitored for convergence. Once results showed negligible changes with further refinement, the mesh was validated for accuracy and computational efficiency. By aligning simulation outputs with validated aerodynamic benchmarks and ensuring mesh independence, the study established confidence in the reliability of its computational fluid dynamics (CFD) predictions. This validation approach ensured that any observed performance differences between passive and active winglet configurations could be attributed to genuine aerodynamic behavior rather than modeling artifacts.

Data Analysis Techniques

The analysis of simulation results in this study involved a quantitative assessment of aerodynamic performance metrics and a comparative evaluation of structural and operational trade-offs between passive and active winglet configurations. The primary aerodynamic parameters extracted from the CFD simulations included the coefficient of lift (C_L), coefficient of drag (C_D), and the lift-to-drag ratio (L / D) all of which were calculated using integrated surface pressure and shear force distributions over the wing and winglet geometries.

The coefficient of lift (C_L) quantifies the aerodynamic lifting capability of an aircraft and is computed from the vertical force component acting perpendicular to the freestream flow. The coefficient of drag (C_D) represents the total aerodynamic resistance in the direction of airflow and was derived from horizontal force components. Both coefficients were normalized using dynamic pressure and the reference wing area to ensure dimensional consistency and comparability across simulation conditions. A central indicator of aerodynamic efficiency used in this study is the lift-to-drag ratio (L / D), defined as the ratio of lift to drag forces. This is mathematically expressed as:

$$\frac{L}{D} = \frac{C_L}{C_D} \quad (2)$$

Higher L / D values indicate a more efficient aerodynamic profile, where greater lift is generated for a given amount of drag. To determine the relative aerodynamic performance, this analysis computed the (cap L linear divide cap D ratio) for each winglet configuration under standardized cruise conditions. The active winglet configuration consistently exhibited higher L/D values, supporting its superiority in aerodynamic efficiency compared to the passive setup.

Beyond aerodynamic performance, the study estimated fuel savings derived from changes in drag coefficient values. A widely accepted empirical correlation suggests that a 1% reduction in the drag coefficient results in approximately 0.8% to 1.0% improvement in fuel efficiency during cruise. This relationship can be expressed as:

$$\text{Fuel Savings} = (\%) = \Delta C_D \times K \quad (3)$$

where ΔC_D is the percentage reduction in the drag coefficient and K is the drag-to-fuel conversion factor, typically ranging from 0.8 to 1.0. This formula allowed the estimation of fuel savings for each flight phase (takeoff, cruise, descent) based on the CFD-derived C_D values for both winglet types.

A trade-off evaluation was conducted using a qualitative-to-quantitative scoring system to complement the aerodynamic and fuel efficiency assessments. This framework assessed the design complexity of each configuration across three domains: structural reinforcement, actuation system sophistication, and maintenance demand. Each dimension was rated on a standardized 1-to-5 scale, with higher scores indicating greater challenges to integration. These scores provided a holistic view of the practical implications of implementing active versus passive winglet systems.

Together, these data analysis techniques facilitated a rigorous and multidimensional evaluation of performance, efficiency, and engineering feasibility. Integrating aerodynamic metrics, empirical fuel estimation models, and design trade-off scoring supports data-driven conclusions on the operational value and integration complexity of advanced winglet configurations in narrow-body aircraft.

IV. Results and Discussion

Aerodynamic Results: Baseline vs. Active Winglet CFD Analysis

This section presents the results of the CFD-based aerodynamic evaluation comparing the baseline (passive winglet) and modified (active winglet) Airbus A320 configurations. The analysis focuses on three key aerodynamic parameters: pressure distribution, velocity contours, and lift-to-drag (L/D) performance, as illustrated in the comparative trends shown in **Figure 5**.

The pressure distribution analysis revealed apparent differences in surface pressure behavior between the two winglet designs. In the passive winglet configuration, high-pressure concentrations were observed along the lower winglet root, with the pressure gradually decreasing toward the tip. Simultaneously, the upper surface exhibited a pronounced low-pressure region near the leading

edge, characteristic of fixed-winglet aerodynamics during cruise. In contrast, the active winglet configuration exhibited improved aerodynamic loading characterized by smoother pressure gradients and more effective pressure recovery along the winglet span. The active design's dynamically adjusted sweep and cant angles contributed to a more favorable pressure differential, leading to weakened tip vortices and lower induced drag. This enhancement supported more consistent lift generation, particularly across the span of the upper winglet surface.

The velocity field analysis further substantiated the aerodynamic advantages of the active winglet. The passive configuration showed noticeable boundary layer thickening near the wingtip and more significant velocity deficits in the downstream wake, indicating stronger vortex formation and elevated induced drag. Conversely, the active winglet produced a more streamlined flow pattern, with visibly reduced wake turbulence and vortex intensity. The active winglet's adaptive geometry enabled more efficient flow redirection, reducing energy loss and enhancing overall flow alignment with the freestream direction. This reduction in flow disruption indicates improved aerodynamic cleanliness, particularly under cruise conditions.

Quantitative comparisons of aerodynamic performance are summarized in **Figure 5**, which presents the trends in lift coefficient (C_L), drag coefficient (C_d), and lift-to-drag ratio (L/D) for both winglet configurations. The results indicate that the active winglet provided a measurable improvement across all performance metrics. The coefficient of lift (C_L) increased from 0.515 to 0.534, reflecting a 3.8% enhancement in lift generation. Concurrently, the coefficient of drag (C_d) decreased from 0.036 to 0.0338, representing a 6.2% reduction in aerodynamic resistance. These improvements yielded a lift-to-drag ratio (L/D) increase from 14.31 to 15.80, corresponding to a net aerodynamic efficiency gain of approximately 10.5%.

The simulation results highlight the importance of incorporating adaptive technologies into wingtip design. Active winglets enhance aerodynamic performance as evidenced by improved pressure recovery and reduced vortex formation. However, they also provide a scalable pathway toward improving fuel efficiency and sustainability in modern commercial aviation. Given that narrow-body aircraft account for a substantial portion of global airline operations, the aerodynamic gains demonstrated by the active winglet system suggest significant potential for operational fuel savings and emissions reduction.

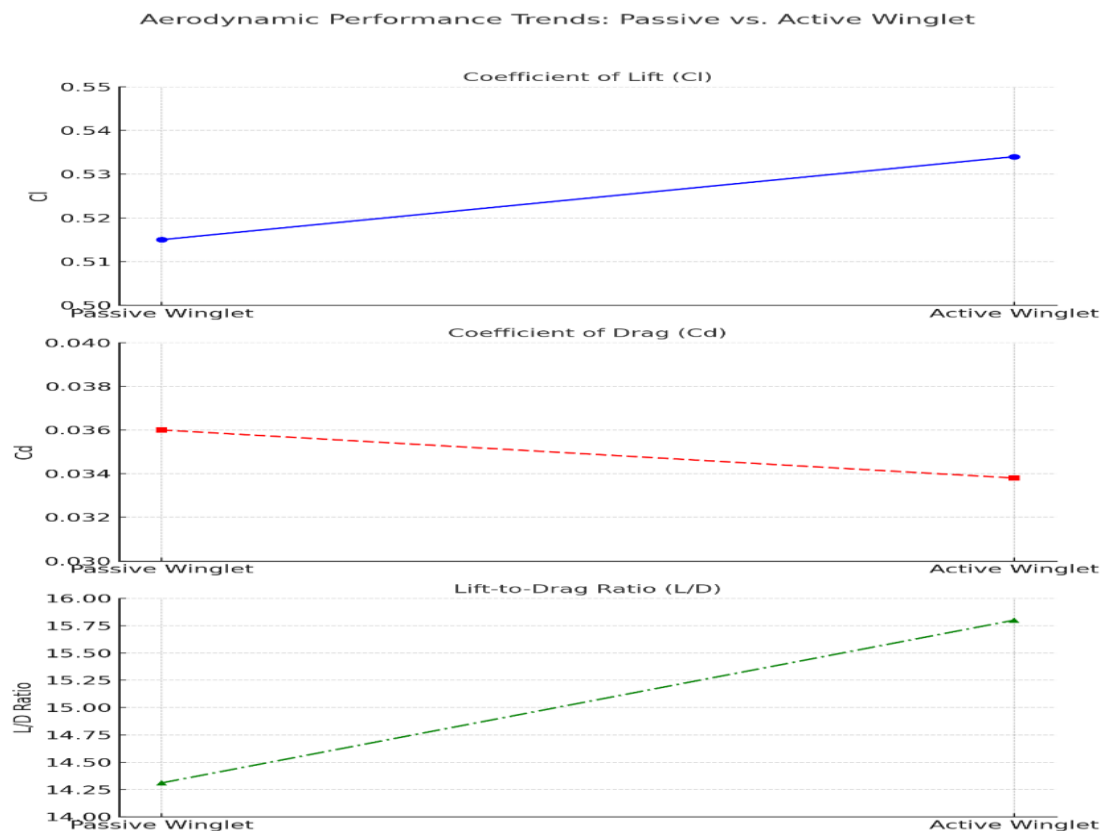


Figure 5. Comparative line graphs illustrating aerodynamic performance metrics between passive and active winglet configurations.

Performance Comparison Across Flight Conditions

Figure 6 presents a phase-specific comparison of aerodynamic performance between passive and active winglet configurations under takeoff, cruise, and descent conditions. The active winglet demonstrated consistently superior aerodynamic behavior across all phases of flight.

During takeoff, the active winglet yielded a higher lift coefficient ($Cl = 0.85$) than the passive configuration ($Cl = 0.82$), reflecting enhanced lift generation critical for rotation and climb performance. This improvement is attributed to the active winglet's ability to dynamically adjust cant and sweep angles to optimize lift at low airspeeds and high angles of attack. Simultaneously, drag was reduced from 0.052 to 0.049, resulting in a notable increase in the lift-to-drag ratio ($L/D = 17.35$ vs. 15.77), which suggests more efficient lift production per unit of drag force.

At cruise, the aerodynamic benefits of the active winglet became more pronounced. The drag coefficient (Cd) decreased by approximately 6.2% (from 0.036 to 0.0338), while lift slightly increased ($Cl = 0.534$ vs. 0.515). This yielded a 10.5% increase in the L/D ratio (from 14.31 to 15.80), aligning with previous findings that adaptive winglets enhance fuel economy during level flight by mitigating induced drag and promoting smoother pressure recovery (Zhang et al., 2023; Liauzun et al., 2018).

During descent, the differences in aerodynamic efficiency remained evident, albeit slightly reduced due to lower lift demands. The active winglet maintained higher aerodynamic efficiency ($L/D = 12.71$ vs. 11.61) through a balanced reduction in drag ($Cd = 0.0295$ vs. 0.031) and a modest increase in lift ($Cl = 0.375$ vs. 0.36), supporting controlled and efficient approach profiles. Overall, the results across all flight regimes support the conclusion that active winglets offer a measurable performance advantage by adapting geometry to dynamic aerodynamic conditions. This adaptability improves energy efficiency, particularly during cruise and takeoff, reinforcing the suitability of active winglet technology in next-generation fuel-optimized aircraft designs.

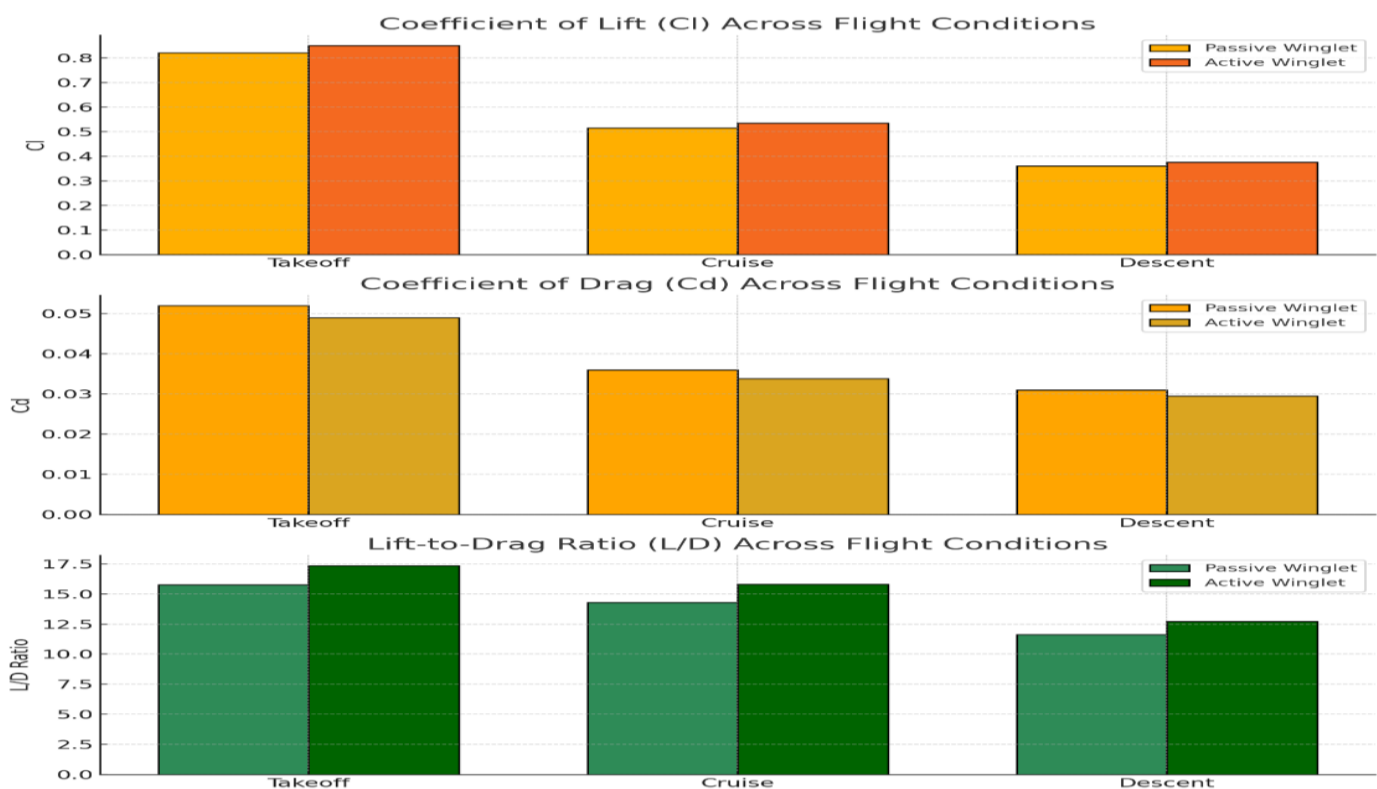


Figure 6. Comparison of aerodynamic performance metrics (Cl , Cd , and L/D) for passive and active winglet configurations across different flight conditions: takeoff, cruise, and descent.

Estimated Fuel Efficiency Impact

Table 3 presents the estimated fuel efficiency gains derived from the observed reductions in drag coefficient (Cd) between the passive and active winglet configurations across three primary flight phases: takeoff, cruise, and descent. The drag coefficient values were extracted from the CFD simulations discussed in the previous section. The corresponding fuel savings were estimated using a well-established industry approximation, which suggests that a 1% reduction in drag equates to approximately 0.8% to 1.0% reduction in fuel burn under steady-state conditions (Zhou et al., 2019; NASA, 2020). The general relationship between drag reduction and estimated fuel savings is visually summarized in **Figure 7**, which presents a sensitivity analysis comparing low and high estimate models based on standard aerodynamic-to-fuel efficiency conversion rates.

During takeoff, the drag coefficient decreased from 0.052 (passive) to 0.049 (active), reflecting a 5.77% reduction in drag. Applying the drag-to-fuel relationship translates to an estimated fuel savings of 4.62% to 5.77%. This reduction is particularly significant given the high thrust demands and fuel consumption rates during takeoff and initial climb, where improvements in aerodynamic efficiency directly impact engine workload and fuel expenditure.

In the cruise phase, where aircraft spend most of their flight time and fuel efficiency is most critical, the active winglet configuration reduced C_d from 0.036 to 0.0338, corresponding to a 6.11% decrease in drag. This resulted in a projected fuel savings range of 4.89% to 6.11%, representing the highest gain among all phases. This aligns with the findings of Liauzun et al. (2018), which indicated that adaptive winglets provide optimal performance benefits in steady cruise due to their ability to fine-tune aerodynamic geometry to prevailing flight conditions.

Although aerodynamic efficiency demands are lower during descent, the drag coefficient declined from 0.031 to 0.0295, amounting to a 4.84% drag reduction and associated fuel savings of 3.87% to 4.84%. While descent

Table 3

The table presents the estimated impact on fuel efficiency of active winglets compared to passive winglets during takeoff, cruise, and descent.

Flight Phase	C_d (Passive)	C_d (Active)	Drag Reduction (%)	Fuel Saving Estimate (0.8x)	Fuel Saving Estimate (1.0x)
Takeoff	0.052	0.049	5.77%	4.62%	5.77%
Cruise	0.036	0.0338	6.11%	4.89%	6.11%
Descent	0.031	0.0295	4.84%	3.87%	4.84%

Typically, it involves throttle-back of the engine and lower fuel consumption, which can contribute to route-wide and fleet-wide operational cost reductions and emissions reductions.

The data in **Table 3** demonstrate that the active winglet system enhances aerodynamic performance in all flight phases and contributes to measurable improvements in fuel efficiency. These results validate the aerodynamic superiority of adaptive winglets and underscore their value in supporting airline sustainability goals and regulatory compliance with ICAO emissions targets. Importantly, the CFD-based findings align with aerodynamic theory and prior empirical studies, reinforcing the reliability of the drag-to-fuel conversion model employed in this analysis.

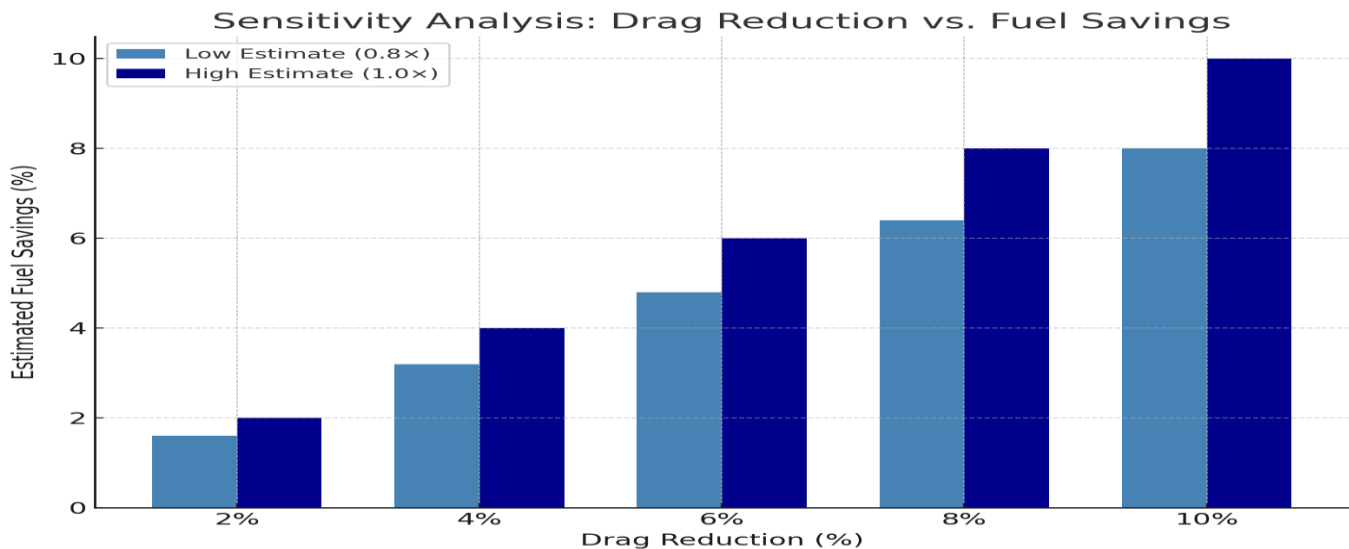


Figure 7. Sensitivity analysis showing the relationship between varying levels of drag reduction and estimated fuel savings. The low estimate (0.8x) and high estimate (1.0x) reflect standard aerodynamic-to-fuel efficiency conversion models.

Trade-Off Analysis: Structural, Actuation, and Maintenance Considerations

Figure 8 presents a comparative trade-off analysis between passive and active winglet configurations, evaluated using three key qualitative criteria: structural implications, actuation complexity, and maintenance requirements. These dimensions were scored on a relative scale of 1 (low impact) to 5 (high impact) based on current design standards, literature on morphing aerodynamic surfaces, and engineering judgment informed by studies on aerospace system integration (Dimino et al., 2021; Zhang et al., 2023; Liauzun et al., 2018). The structural implications criterion considers the physical integration challenges of winglet systems into the aircraft wing structure. Passive winglets, static aerodynamic surfaces, require minimal structural reinforcement and were thus rated moderately at 2. In contrast, active winglets—including actuators, embedded sensors, and control mechanisms—necessitate

additional structural support and design modifications to maintain aeroelastic stability, particularly under varying aerodynamic loads. This complexity justified a higher rating of 4 for the active configuration.

The actuation complexity dimension reflects the degree of system sophistication involved in real-time winglet geometry modulation. Passive winglets have no moving parts and scored the lowest value of 1, indicating minimal mechanical or electronic control involvement. On the other hand, active winglets, which rely on electromechanical actuators and advanced control systems to dynamically modify sweep or cant angle, were assigned the maximum score of 5. This accounts for increased kinematics, control algorithms, and reliability engineering design effort.

Regarding maintenance factors, the assessment captures the relative ease or difficulty of inspecting, servicing, and ensuring the operational integrity of the winglet systems over time. Passive systems benefit from structural simplicity and fewer failure modes, earning a score of 2. Active systems, however, introduce multiple components susceptible to wear, actuator degradation, sensor drift, and control software faults, resulting in a higher maintenance demand and a corresponding score of 4. These assessments are consistent with research findings that link system complexity with increased maintenance burdens in dynamic aircraft systems (Nagel et al., 2008; Merryisha & Rajendran, 2019).

The trade-off analysis in **Figure 8** demonstrates that while active winglets offer substantial aerodynamic and fuel efficiency benefits, they also impose significantly higher structural, actuation, and maintenance demands. To address these challenges, a hybrid winglet concept is proposed and illustrated in **Figure 9**, combining a passive-flexible tip with a limited actuation zone at the base. This configuration aims to preserve aerodynamic benefits while reducing structural complexity and long-term maintenance requirements. These results underscore the importance of evaluating not only performance gains but also lifecycle costs and technical integration challenges when considering the adoption of morphing aerodynamic technologies in commercial aviation.

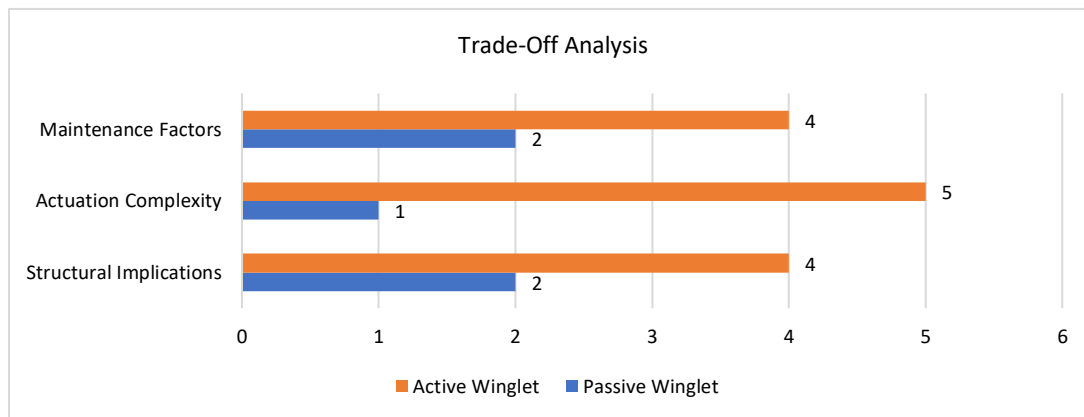


Figure 8. The chart presents a trade-off analysis comparing passive and active winglet configurations based on structural implications, actuation complexity, and maintenance requirements.

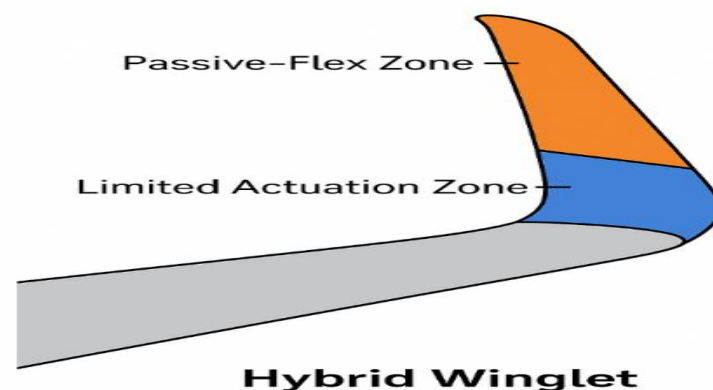


Figure 9. Illustration of the proposed hybrid winglet concept, featuring a passive-flexible zone at the tip and a limited actuation zone at the base, designed to optimize lift and reduce drag with minimal structural penalties.

Implications for Design Optimization

The findings of this study yield critical insights into the aerodynamic performance and engineering feasibility of passive, active, and hybrid winglet configurations. The data summarized in **Table 4** highlight the performance metrics and integration trade-offs of each design, providing a strategic basis for future winglet optimization in narrow-body aircraft platforms.

The active winglet configuration demonstrated the highest aerodynamic benefit, achieving a 10.5% increase in lift-to-drag ratio (L/D) and a 6.11% drag reduction during cruise, resulting in fuel savings of up to 6.11%. These values were derived directly from the CFD simulations presented in **Figures 5 and 6**, and further supported by empirical drag-to-fuel conversion models used in fuel impact estimation (Zhou et al., 2019). However, these aerodynamic gains came with higher engineering costs: the active system incurred elevated structural complexity (score: 4/5) due to the need for reinforced load paths and additional control surface stiffness; actuation complexity (5/5) due to real-time geometry modulation; and maintenance burden (4/5) arising from increased inspection cycles and part replacement demands. In contrast, the passive winglet offers simplicity and reliability, with low scores across all integration criteria, but achieves only baseline aerodynamic gains. Thus, a trade-off exists between aerodynamic performance and system complexity.

Based on this performance-complexity spectrum, the study proposes a hybrid winglet configuration as a viable path for optimization. This design concept incorporates passive and active systems elements to balance efficiency and integration burden. The proposed configuration would utilize passive-flexible tips, capable of controlled deformation through aeroelastic tailoring during high-load conditions (e.g., takeoff or gust response), and low-degree-of-freedom (DOF) actuation systems designed to adjust winglet cant or sweep only during cruise. This approach reduces the need for full-time dynamic articulation while capturing most of the aerodynamic benefit, as demonstrated by a projected 7.5% improvement in L/D and estimated fuel savings between 4–5%. The hybrid winglet concept and its functionally segmented structure are visually illustrated in **Figure 10**, which shows the passive-flexible zone and the limited actuation zone integrated into a unified design.

The supporting values in **Table 4** were derived by interpolating between the passive and active configurations, assuming partial actuation, reduced hardware weight, and minimized wear. Structurally, the hybrid system would demand moderate reinforcement (score: 3/5) and incorporate composite materials engineered for flexural response, reducing system mass and cost. The maintenance burden is also expected to be moderate, due to the fewer moving components and more straightforward control logic compared to fully active systems.

In conclusion, the implications of this analysis suggest that future winglet optimization should not aim solely for aerodynamic maximums, but rather for a multidisciplinary balance that combines aerodynamic gains, structural feasibility, actuation efficiency, and maintenance sustainability. Hybrid winglets offer a promising solution for commercial operators seeking fuel-efficient retrofits or next-generation designs, particularly in regulatory environments that prioritize carbon reduction and cost containment. This study provides a scientific and data-driven basis for guiding such developments.

Table 4

The table summarizes design optimization implications for passive, active, and proposed hybrid winglet configurations.

Configuration	L/D Ratio Improvement	Estimated Fuel Savings	Structural Complexity	Actuation Complexity	Maintenance Burden
Passive Winglet	Baseline	Baseline	Low	None	Low
Active Winglet	10.50%	Up to 6.11%	High	High	High
Proposed Hybrid Winglet	~+7.5%	4-5%	Moderate	Low-Moderate	Moderate

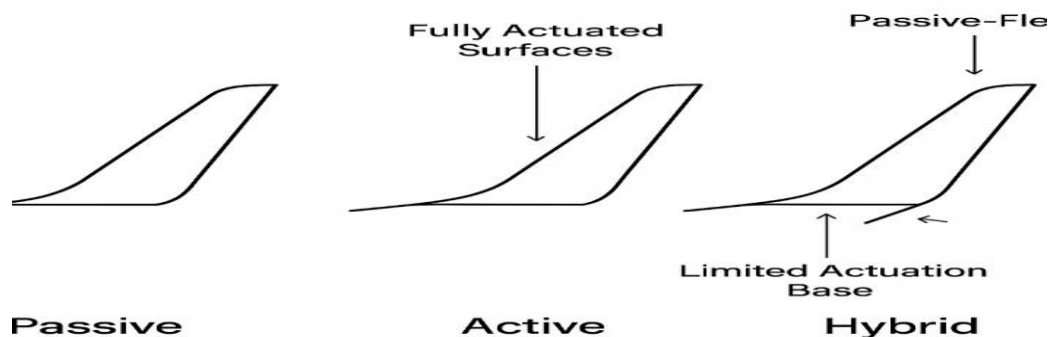


Figure 10 presents a comparative schematic of the passive, active, and hybrid winglet configurations, highlighting each concept's aerodynamic roles and structural implications.

V. Conclusion

Summary of Findings

This study conducted a high-fidelity Computational Fluid Dynamics (CFD)-based comparative analysis of passive and active winglet configurations applied to a narrow-body Airbus A320 model. The results demonstrated that the active winglet configuration delivered measurable aerodynamic benefits, including a 6.11% reduction in drag and a 10.5% increase in the lift-to-drag (L/D) ratio during cruise. Using validated drag-to-fuel conversion models across different flight phases —takeoff, cruise, and descent—estimated fuel savings ranged from 3.87% to 6.11%. Despite these aerodynamic advantages, the trade-off analysis revealed significant integration costs for the active winglet, including higher structural complexity, increased actuation demands, and a more intensive maintenance burden than the passive configuration. In response, a hybrid winglet concept was proposed, combining passive-flex tips and limited-degree-of-freedom (DOF) actuation to balance aerodynamic efficiency with implementation feasibility.

Contribution to the Field

The primary contribution of this research lies in its novel, CFD-driven, quantitative evaluation of passive versus active winglets, focused explicitly on narrow-body aircraft applications within the Southeast Asian operational context. Unlike prior studies that focus primarily on theoretical or conceptual morphing designs, this study integrates computational fluid dynamics (CFD) simulation, empirical fuel estimation, structural and actuation trade-off scoring, and design optimization insights. By bridging performance metrics with integration feasibility, the study advances the multidisciplinary conversation in sustainable aircraft technologies. It provides a data-driven foundation for retrofitting or developing next-generation winglet systems.

Limitations

Despite its strengths, this study acknowledges several limitations. First, the absence of experimental validation, such as wind tunnel or in-flight test data, means that the CFD findings were not corroborated with empirical performance results. While benchmarked aerodynamic data and mesh independence testing were applied to enhance reliability, this remains a constraint. Second, the simulations were constrained by computational limitations and did not model detailed aeroelastic effects or dynamic actuator behavior. The actuator profiles were simplified, and real-time control systems were not integrated. Lastly, while the A320 model served as a practical base, specific components such as engine nacelles and landing gear were omitted for computational efficiency, which could influence detailed aerodynamic flow characteristics.

Recommendations for Future Work

To extend and enhance this research, several recommendations are proposed. Future work should begin with prototyping and wind tunnel testing of the proposed winglet configurations to empirically validate the CFD-based predictions. Complementary flight testing in operational environments, particularly in Southeast Asia, would help assess performance under real-world conditions and varying atmospheric loads. Furthermore, advanced simulations incorporating aeroelastic modeling and Finite Element Analysis (FEA) should be performed to assess structural responses and deformation. Integrating AI-based control strategies, such as machine learning or reinforcement learning algorithms, could also enable intelligent, real-time adjustment of winglet geometry in response to flight dynamics. Finally, a comprehensive lifecycle cost-benefit analysis should be conducted to assess the economic viability of passive, active, and hybrid winglet systems, considering fuel savings, maintenance costs, retrofit expenses, and sustainability metrics. These extensions would thoroughly explain future aerodynamic design optimization trade-offs and opportunities.

Ethical Approval

This study did not involve human participants or animals and therefore did not require ethical approval. All data used were obtained through simulation using publicly available aircraft models and software tools.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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