

Computational Fluid Dynamics Analysis of Wing-Tip Modifications on Tapered Wings to Enhance Aerodynamic Performance of Unmanned Aerial Vehicles

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Abstract: Unmanned Aerial Vehicles (UAVs) are widely deployed in applications that require high aerodynamic efficiency, extended endurance, and precise control. The aerodynamic performance of UAVs is strongly influenced by wing design, particularly at the wingtips, where intense vortices can generate significant induced drag and promote early stall. This study employs a full-factorial design of experiments (DoE) combined with computational fluid dynamics (CFD) simulations using the $k-\omega$ SST turbulence model to investigate the effect of wing tip modifications on various angle of attack (AoA). The results indicate that the maximum lift coefficient occurs at an AoA of 10° for all wingtip configurations, with the rounded-edge wingtip achieving the highest value ($C_l = 0.125$). The drag coefficient increases gradually from AoA 0° to 10° , followed by a sharp rise up to 15° , indicating early stall. The highest lift-to-drag ratio is obtained at AoA = 5° , where the rounded-edge wingtip demonstrates superior aerodynamic efficiency ($C_l/C_d = 20.4$). Analysis of the pitching moment coefficient reveals a nose-down tendency at low to moderate AoA, transitioning to an aggressive nose-up behavior at higher angles of attack. Overall, the rounded-edge wingtip provides the most favorable aerodynamic performance for fixed-wing UAVs, offering improved efficiency and stable longitudinal characteristics within low to moderate AoA operating regimes.

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INTRODUCTION

Unmanned Aerial Vehicle (UAV) has become increasingly significant and is widely deployed in various applications, ranging from military operations to agricultural monitoring. UAV deployment demands high aerodynamic efficiency, extended endurance (Chandra & Misra, 2023; Unegbu & Yawas, 2025), precise control, quieter operation, and safer, more reliable flight (Inan & Ceylan, 2024; Pathak, 2025). Wingtip modifications ranging from simple winglets to complex bio-inspired and morphing geometries offer a means to address these demands. However, these benefits are counterbalanced by new challenges, including increased structural complexity, potential aeroelastic instabilities, and the need for advanced monitoring and control systems. Thus, a comprehensive understanding of wingtip design is essential for the next generation of UAVs, where performance, safety, and operational flexibility must be harmonized (Fam et al., 2023; Shin et al., 2024; Sivanandi et al., 2025; Winarto et al., 2018).

The aerodynamic characteristics of UAVs are distinct from those of manned aircraft, primarily due to their operation at low Reynolds numbers, smaller physical scales, and mission-specific requirements. This low Reynolds number regime renders UAVs highly sensitive to vortical flows.

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Consequently, the selection of an appropriate wingtip design is crucial for managing vortex formation and effectively reducing induced drag.

These factors necessitate specialized aerodynamic design and analysis approaches. Computational Fluid Dynamics (CFD) has become an indispensable tool in UAV research, enabling detailed simulation of complex flow phenomena, iterative design optimization, and the development of aerodynamic databases for control and stability analysis (Orozco et al., 2025; Prasetyo et al., 2025; Yashwanth et al., 2024). Turbulence modelling plays a critical role in determining the accuracy of computational fluid dynamics (CFD) simulations for UAV aerodynamic analysis, particularly in the wingtip region where complex flow phenomena such as laminar-turbulent transition, separation bubbles, and strong vortical structures occur.

Several turbulence models are commonly applied in aerodynamic simulations, including the Spalart-Allmaras (SA), $k-\epsilon$, $k-\omega$ (Chandra & Misra, 2023), Reynolds Stress Model (RSM), and hybrid RANS-LES approaches. Among the available turbulence models, the $k-\omega$ Shear Stress Transport (SST) model has become one of the most widely adopted approaches for aerodynamic simulations involving separated flows and adverse pressure gradients. The SST $k-\omega$ model combines the advantages of the $k-\omega$ formulation near the wall with the $k-\epsilon$ formulation in the free stream, enabling improved prediction of boundary layer behaviour and flow separation compared to simpler models (Karkoulas et al., 2023; Luthfi et al., 2021). Therefore, the SST $k-\omega$ turbulence model is commonly selected for CFD analysis of UAV wingtip aerodynamics, as it offers reliable performance in capturing key aerodynamic characteristics while maintaining manageable computational cost.

The geometry at the wingtip significantly influences vortex formation, induced drag, lift generation, and overall flight efficiency (Farook et al., 2025; P & Junipitoyo, 2022; Sogukpinar, 2018). Strong wingtip vortices typically increase induced drag and reduce the lift-to-drag ratio, which directly affects the endurance and range of UAV systems. As a result, numerous wingtip configurations have been proposed to control vortex behaviour and improve aerodynamic efficiency. Among these configurations, five representative designs are commonly analysed: tapered, sharp edge, rounded edge, sharp edge with long trailing edge, and the ogee tip.

The baseline configuration without a wingtip modification (tapered) represents the simplest design and is often used as a reference in aerodynamic studies. While this configuration offers advantages in terms of structural simplicity, ease of manufacturing, and low production cost, it suffers from strong wingtip vortex formation. These vortices increase induced drag and reduce the lift-to-drag ratio, leading to lower aerodynamic efficiency and limited flight endurance (Gharbia et al., 2023; Manjunath et al., 2020).

Sharp edge wingtips configuration can increase lift generation, with some studies indicating a potential lift improvement of up to approximately 23% under certain conditions (Zhang et al., 2022). However, the sharp edge geometry produces multiple interacting vortices that create a complex wake structure. This behaviour tends to increase induced drag, generate higher aerodynamic noise, and reduce flow stability, particularly at high angles of attack. As a result, although the sharp edge design offers higher lift potential, it often compromises aerodynamic efficiency and stability.

Rounded edge wingtips configuration typically produces a single primary vortex with smoother roll-up behaviour, which reduces induced drag and improves the lift-to-drag ratio (Gharbia et al., 2023). In addition, rounded tips offer more stable aerodynamic characteristics and improved stall behaviour

compared to sharp edge designs (Zhang et al., 2022). Therefore, rounded edge designs are widely considered a balanced solution between aerodynamic efficiency and practical implementation.

More advanced configurations, such as the sharp edge with a long trailing edge and the ogee tip, aim to further optimize vortex distribution and aerodynamic efficiency. The sharp edge-long trailing edge design distributes vortices more evenly and can reduce induced drag, although it may introduce structural complexity and additional weight (Gueraiche & Popov, 2017). The ogee tip, characterized by its double-curvature geometry, has been reported to improve drag reduction and aerodynamic efficiency among the compared designs (Yohanes et al., 2025). While advanced wingtip designs offer superior aerodynamic performance, they also involve greater structural and manufacturing challenges (Rodríguez-Sevillano et al., 2023).

Given the strong influence of wingtip design on aerodynamic characteristics, a systematic evaluation of baseline and modified geometries under representative operating conditions provides valuable insight into flow behavior, vortex structures, and performance trade-offs, ultimately identifying configurations that maximize efficiency while preserving stability and controllability. Such investigations contribute to the development of UAV platforms capable of longer endurance, improved manoeuvrability, and enhanced mission effectiveness.

Despite extensive research on wingtip devices, several critical gaps remain in the current literature. Most previous studies primarily focus on optimizing a single type of winglet geometry or limited parameter variations, such as cant angle or taper ratio, without conducting a systematic comparison across multiple distinct wingtip configurations (Nikolaou et al., 2025; Xiao & Sun, 2024). While comparative studies exist, they are often restricted to a small number of configurations (e.g., simple, blended, and fence winglets) and specific flight conditions, particularly at low Reynolds numbers (Putro et al., 2021). Moreover, existing reviews highlight inconsistencies in findings and emphasize the need for broader comparative frameworks and deeper aerodynamic analysis of vortex behaviour and induced drag mechanisms (Liu et al., 2021).

In addition, although it is well established that wingtip devices improve aerodynamic efficiency by reducing induced drag and suppressing wingtip vortices (Chandra & Misra, 2023), there is still limited research that evaluates multiple wingtip configurations within a unified computational framework for UAV applications, particularly for tapered wing geometries. This gap is significant because UAV performance is highly sensitive to aerodynamic efficiency, especially under low Reynolds number operating conditions (Ahmed et al., 2024).

Therefore, this study aims to systematically investigate and compare five different wingtip configurations including tapered, sharp edge, rounded edge, sharp edge with long trailing edge, and ogee tip using computational fluid dynamics. The selection of these configurations is intended to represent a diverse range of commonly used and innovative wingtip designs, enabling a more comprehensive evaluation of their aerodynamic performance. The specific objective of this research is to analyse the effects of each configuration on key aerodynamic parameters, including lift coefficient, drag coefficient, and lift-to-drag ratio, as well as flow characteristics such as vortex formation.

The novelty of this work lies in providing a comprehensive comparative analysis of multiple wingtip configurations within a single consistent CFD framework, which is still limited in existing studies. Furthermore, this research contributes to the development of UAV aerodynamic design by offering quantitative insights into the relative effectiveness of different wingtip geometries, thereby

supporting more informed design decisions for improving UAV efficiency, endurance, and operational performance.

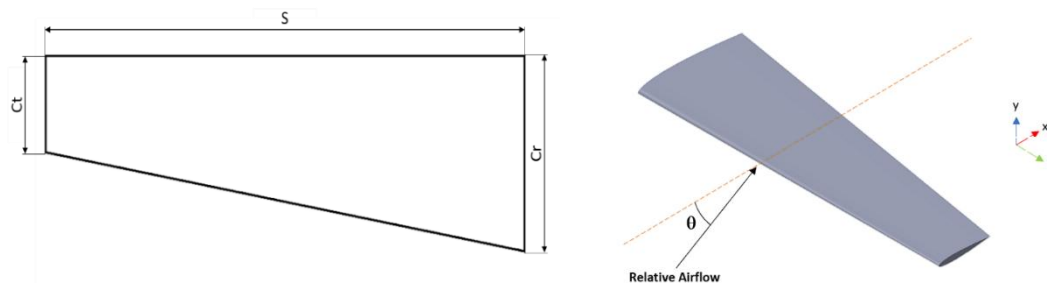
RESEARCH METHOD

Model Design

The wing geometry employed in this study is a tapered wing, as illustrated in Figure 1. The taper ratio used is 0.5. This ratio is obtained from the comparison between the tip chord (c_t) and the root chord (c_r). The wing profile (airfoil) utilized in this simulation is NACA 6412. The complete geometric specifications are summarized in Table 1.

This study analysis the aerodynamic performance of the wing at several angles of attack (θ) ranging from 0° to 15° . Each simulation was conducted with an increment of five degrees. In addition, various types of wingtips, as shown in Figure 3, were applied to reduce drag caused by vortex drag.

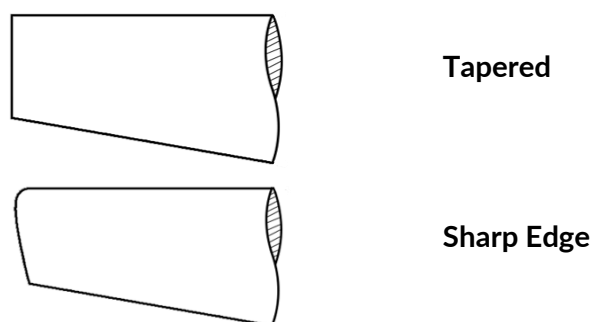
Figure 1. The planform shape of the wing & 3D models with Angle of Attack

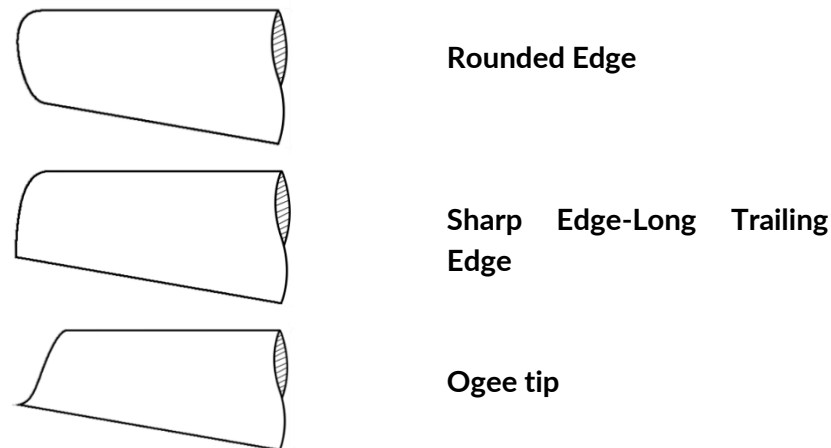


Tabel 1. Model parameters of wing

Parameters	Values
Wingspan, S (mm)	750
Root Chord, C_r (mm)	260
Tip chord, C_t (mm)	130
Mean Aerodynamic Chord (MAC)	202.22
Aspect ratio (AR)	7.69
Taper Ratio (λ)	0.5
Airfoil	NACA6412

Figure 2. Types of Wingtips

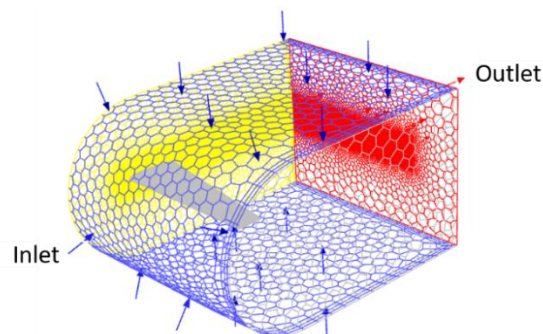




Numerical Setup

The three-dimensional (3D) geometry was subsequently exported to a meshing software package, where it was discretized using an unstructured mesh configuration. To enhance the accuracy of the numerical simulation, local mesh refinement was applied in the wingtip region, where the flow is prone to generating strong vortical structures and complex aerodynamic phenomena frequently occur. The resulting mesh model, illustrated in Figure 3, was then imported into the simulation environment for pre-processing and numerical solution procedures.

Figure 3. Schematic diagram of the model within the flow field domain



In conducting the Computational Fluid Dynamics (CFD) simulation to evaluate the aerodynamic characteristics of the wing, the $k-\omega$ Shear Stress Transport (SST) turbulence model was employed. This model was selected due to its superior capability in accurately predicting near-wall flow behaviour, particularly under flow separation conditions. The $k-\omega$ SST model integrates the advantages of both the $k-\epsilon$ and $k-\omega$ turbulence models, enabling effective treatment of laminar-to-turbulent transition and providing reliable results in regions characterized by strong adverse pressure gradients. Therefore, the implementation of this turbulence model is highly appropriate for aerodynamic analysis, allowing for more realistic predictions of pressure distribution, lift, drag, and aerodynamic moment acting on the wing.

Table 2. Detail preprocessing

Parameters	Values
Models	Viscous: k- ω SST
Material (air)	Density: constant Viscosity: constant
Boundary conditions	Velocity Inlet: 35 m/s Pressure outlet Wing: Wall Symmetry
Report definitions	Drag Coefficient Lift Coefficient Moment Coefficient
Solution Initialization	Standard initialization

RESULTS AND DISCUSSION

Influence of Wingtips on Lift Coefficient

The increase in the lift coefficient with increasing AoA up to a maximum value at 10° for all wingtip configurations indicates aerodynamic characteristics consistent with classical wing theory up to near-stall conditions. At low to moderate AoA, an increase in AoA leads to a greater pressure difference between the upper and lower wing surfaces, thereby generating a higher lift force.

The differences in maximum Cl values among the wingtip configurations indicate a significant influence of wingtip geometry on flow distribution and wingtip vortex strength. The rounded-edge wingtip configuration produces the highest Cl value (0.125362880), which can be attributed to its ability to weaken wingtip vortex intensity and delay flow separation in the tip region. The curved geometry allows for smoother flow transition, reduces sharp pressure gradients, and maintains attached flow at higher AoA.

In contrast, the sharp-edged wingtip configuration tends to generate stronger vortices due to larger pressure gradients at the wingtip. These intense vortices increase induced losses and accelerate the onset of localized flow separation, thereby limiting the growth of the lift coefficient even as AoA continues to increase.

The occurrence of peak Cl at AoA = 10° for all configurations indicates that this angle represents the optimal operational limit before flow separation effects become dominant. At higher AoA, further increases in AoA are no longer accompanied by significant lift enhancement due to the expansion of separation regions and increased vortex strength, which effectively reduce lift efficiency. In the context of UAV applications, this behaviour suggests that wingtip designs capable of controlling wingtip vortices and maintaining flow stability at moderate AoA, such as the rounded-edge wingtip, offer advantages in terms of lift enhancement, aerodynamic efficiency, and a safer stall margin, particularly during cruise and light manoeuvring phases.

Figure 4. Coefficient of lift of various wingtips on various AoA

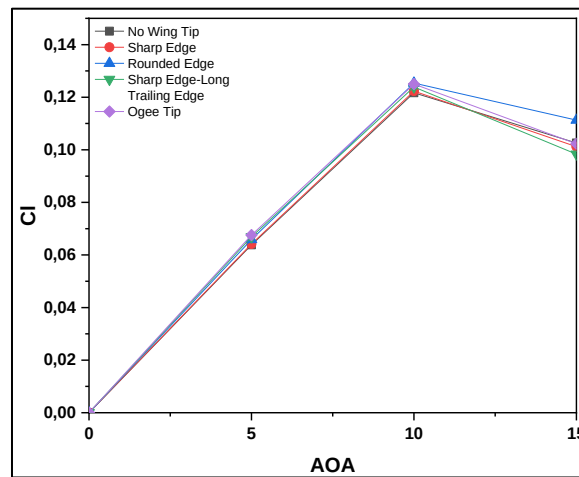


Table 3. Coefficient of lift of various wingtips on various AoA

Wingtip	AoA			
	0	5	10	15
No Wing Tip	-0.000000325	0.063833351	0.121677640	0.102588660
Sharp Edge	0.000003692	0.064178026	0.122339910	0.101175100
Rounded Edge	0.000010077	0.065865549	0.125362880	0.111272010
Sharp Edge-long trailing edge	0.000000062	0.066905462	0.123875670	0.098343026
Ogee Tip	0.000007429	0.067576424	0.124981150	0.102283060

Influence of Wingtips on Drag Coefficient

The behaviour of the drag coefficient (C_d) exhibits an increasing trend with increasing AoA for all wingtip configurations. The lowest C_d value occurs at AoA = 0°, reflecting the minimum drag condition when the AoA is small and the flow remains fully attached to the wing surface.

Within the low to moderate AoA range (0°–10°), C_d increases gradually. This is attributed to the rise in induced drag as a direct consequence of increasing lift. As AoA increases, the pressure difference between the upper and lower wing surfaces becomes greater, thereby strengthening the wingtip vortices and increasing aerodynamic losses. In addition, the pressure drag component also begins to increase due to changes in the pressure distribution around the airfoil profile and the wingtip. The sharp increase in C_d at AoA above 10° indicates a significant alteration in the flow structure. At this angle, flow separation effects begin to develop extensively, particularly in the wingtip region and along the upper surface of the airfoil. This flow separation drastically increases form drag and results in a growth of C_d that is no longer linear with respect to AoA. This phenomenon signifies the approach to pre-stall conditions, where drag increases much more rapidly than lift.

Differences in C_d values among the wingtip configurations reflect the effectiveness of each design in controlling wingtip vortices. The rounded-edge wingtip configuration tends to produce lower C_d values at moderate AoA due to its capability to reduce vortex intensity and smooth the flow release at the wingtip. In contrast, wingtip geometries with sharp edges generate stronger vortices, increase induced drag, and accelerate the transition toward flow separation.

In the context of UAV operations, a significant increase in C_d at high AoA directly impacts increased energy consumption and reduced endurance. Therefore, the lower drag performance at cruise AoA demonstrated by the rounded-edge wingtip makes it more suitable for UAV missions requiring high efficiency and extended flight duration.

Figure 5. Coefficient of drag of various wingtips on various AoA

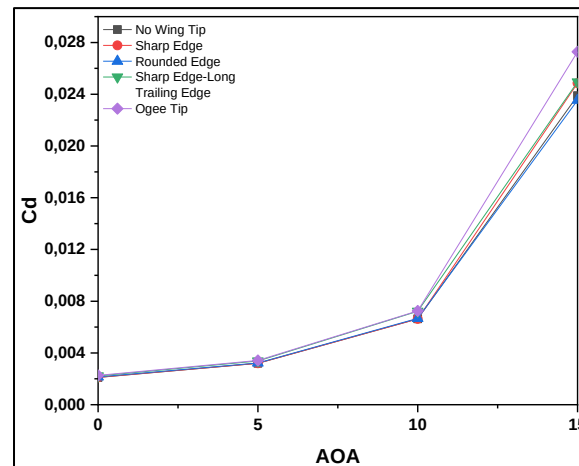


Table 4. Coefficient of drag of various wingtips on various AoA

Wingtip	AoA			
	0	5	10	15
No Wing Tip	0.002105539	0.003198196	0.006639502	0.023888732
Sharp Edge	0.002112554	0.003196906	0.006628031	0.024859915
Rounded Edge	0.002145400	0.003228506	0.006672114	0.023541314
Sharp Edge-long trailing edge	0.002222195	0.003375411	0.007224501	0.024947968
Ogee Tip	0.002267155	0.003423209	0.007246489	0.027285646

Influence of Wingtips on Lift to Drag (C_l/C_d) Ratio

Figure 6 shows the comparison of aerodynamic performance among several configurations across different test conditions. Based on the plotted data, all configurations exhibit a similar trend: a significant increase from 0° to 5° AoA, followed by a gradual decrease toward AoA of 15° .

From the figure, AoA of 0° produces the lowest performance values for all configurations. This indicates that the aerodynamic performance is still limited under the initial operating state. As the operating parameter increases to AoA of 5° , the performance rises sharply and reaches the highest value. This behaviour indicates that the system operates most efficiently at this intermediate condition.

After reaching the peak point, the performance decreases at AoA of 10° and drops significantly at the final condition. This decline may be associated with the increase in aerodynamic drag or the formation of stronger wingtip vortices, which reduce aerodynamic efficiency. The formation of wingtip vortices is known to increase induced drag and consequently reduce the lift-to-drag ratio of a wing.

Although all configurations follow the same general trend, slight differences can be observed between them. Some configurations achieve slightly higher peak values, suggesting better aerodynamic efficiency. These differences may be attributed to geometric variations that influence

the strength of wingtip vortices and the overall lift-to-drag ratio. Modifications such as winglets or optimized wingtip designs are widely used to mitigate vortex formation and improve aerodynamic performance (Chandra & Misra, 2023).

Overall, the results indicate that the tested configurations exhibit optimal aerodynamic performance at AoA of 5°. Beyond this point, aerodynamic losses increase and reduce performance. Therefore, selecting an appropriate operating condition and wing configuration is crucial for maximizing aerodynamic efficiency.

Figure 6. Cl/Cd ratio of various wingtips on various AoA

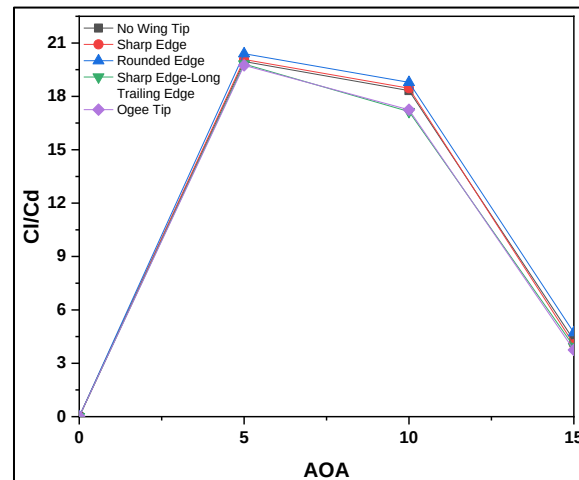


Table 5. Lift to Drag (Cl/Cd) ratio of various wingtips on various AoA

Wingtip	AoA			
	0	5	10	15
No Wing Tip	0.000154135	19.959173548	18.326320533	4.294437227
Sharp Edge	0.001747756	20.075043182	18.457955985	4.069808766
Rounded Edge	0.004697083	20.401250362	18.789080288	4.726669463
Sharp Edge-long trailing edge	0.000028116	19.821426196	17.146606883	3.941925290
Ogee Tip	0.003276825	19.740667863	17.247132394	3.748603203

Influence on Pitching moment

At AoA = 0°, all configurations exhibit Cm values very close to zero, indicating that the aerodynamic forces acting on the wing are nearly balanced and do not generate a significant pitching moment. When the AoA increases to 5°, all configurations begin to show small negative Cm values, indicating a slight nose-down pitching tendency. This behaviour generally occurs when the aerodynamic pressure distribution shifts slightly rearward relative to the reference point.

At AoA = 10°, the negative Cm values become larger for all configurations, indicating an increased nose-down pitching tendency as the AoA increases. Differences among the configurations become more noticeable at this condition. The Sharp Edge–Long Trailing Edge configuration produces the most negative Cm value, suggesting a stronger pressure distribution toward the rear portion of the wing compared with the other configurations.

A more significant change occurs at $\text{AoA} = 15^\circ$, where all configurations exhibit a sudden increase to positive C_m values, indicating a strong nose-up pitching moment. This behaviour may be associated with changes in pressure distribution as the flow begins to become unstable or approaches stall conditions. Under this condition, the Sharp Edge configuration produces the highest C_m value, indicating that this wingtip geometry contributes most strongly to the increase in pitching moment at high angles of attack. In contrast, the Rounded Edge and Sharp Edge–Long Trailing Edge configurations produce relatively lower C_m values.

Overall, the results indicate that wingtip geometry has only a minor influence on pitching moment at low angles of attack (0° – 5°), where all configurations produce very small C_m values. At moderate angles of attack (around 10°), all configurations show negative pitching moments with small variations among them. However, at higher angles of attack (15°), the influence of wingtip geometry becomes more significant, with all configurations shifting to positive pitching moments and the Sharp Edge configuration producing the largest C_m increase. These results suggest that wingtip geometry plays a more important role in pitching moment behaviour at high angles of attack than at low angles of attack.

Figure 7. C_m of various wingtips on different AoA

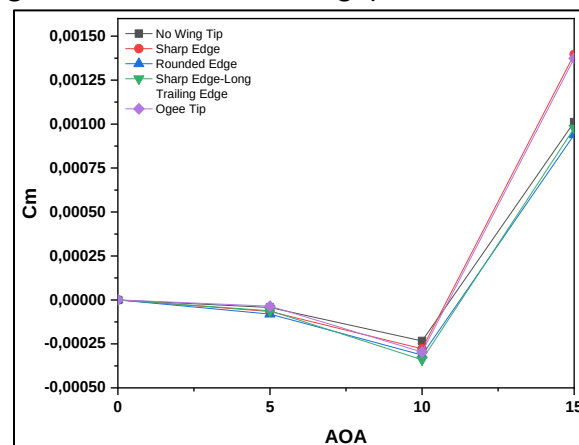


Table 5. C_m Ratio on Various AoA

Wingtip	AoA			
	0	5	10	15
No Wing Tip	0.000000012	-0.000043137	-0.000233002	0.001011351
Sharp Edge	0.000000493	-0.000065823	-0.000277661	0.001396220
Rounded Edge	0.000000308	-0.000080434	-0.000313299	0.000939082
Sharp Edge-long trailing edge	-0.000000192	-0.000061365	-0.000340350	0.000976947
Ogee Tip	0.000000345	-0.000035363	-0.000296208	0.001373482

Wingtip Vortices and Pressure Contour

Figure 8 shows the CFD streamline velocity magnitude results in the UAV wingtip region. The streamline pattern illustrates how the flow turns and forms a wingtip vortex, which is directly related to induced drag and wing efficiency.

A strong vortex is observed at the tapered wingtip, indicated by the sharp curvature of the streamlines. The flow from the pressure side (the lower surface of the wing) moves upward and rolls over the tip. The blue region above the wing indicates low velocity caused by recirculation. The wingtip vortex appears relatively strong, suggesting that the induced drag is comparatively high.

The sharp edge wingtip has a more rounded geometry than tapered wingtip with smoother curvature. The streamlines follow the contour of the tip more smoothly before rolling up. The pressure gradient becomes smoother, and the vortex energy is reduced. As a result, the induced drag is lower compared to the configuration without a wingtip modification. The rounded wingtip helps reduce the vortex strength.

The rounded wingtip configuration introduces a longer tip geometry that allows the streamlines to distribute more gradually along the tip chord. Unlike the previous configurations, the flow does not immediately roll up at the trailing edge. Instead, the vortex forms farther downstream from the wingtip, indicating a smoother flow transition around the tip region. The rounded wingtip effectively increases the wingspan, which improves the spanwise lift distribution and produces a more uniform downwash behind the wing. The smoother downwash distribution and weaker vortex formation indicate improved aerodynamic efficiency. Consequently, the rounded edge wingtip configuration is aerodynamically more efficient than the previous configurations.

An upward deflection of the flow is observed at the sharp edge-long trailing edge wingtip. The streamlines rise and form a more directed vortex control pattern. The wingtip generates a side force that reduces pressure equalization between the pressure and suction sides of the wing. As a result, the vortex becomes smaller and forms farther away from the wing. The addition of a winglet introduces extra structural weight and may increase parasite drag if the design is not optimized.

The velocity magnitude and streamline visualization at the ogee wingtip shows that vortex formation is highly localized near the tip region. Streamlines originating from the pressure side (lower surface of the wing) move upward directly at the wingtip and roll up near the trailing edge, forming a concentrated wingtip vortex. The change in streamline direction occurs rather abruptly, indicating a relatively sharp pressure gradient and strong pressure equalization between the lower and upper surfaces of the wing.

A distinct vortex core can be observed from the tightly rotating streamline patterns near the tip. This indicates that the wingtip vortex remains energetic and well defined, suggesting that the induced drag produced by the wing is still significant. In addition, streamlines above the wing curve downward after passing the tip region, which indicates the presence of noticeable downwash generated by the vortex system.

Figure 8. Streamline velocity on wingtip

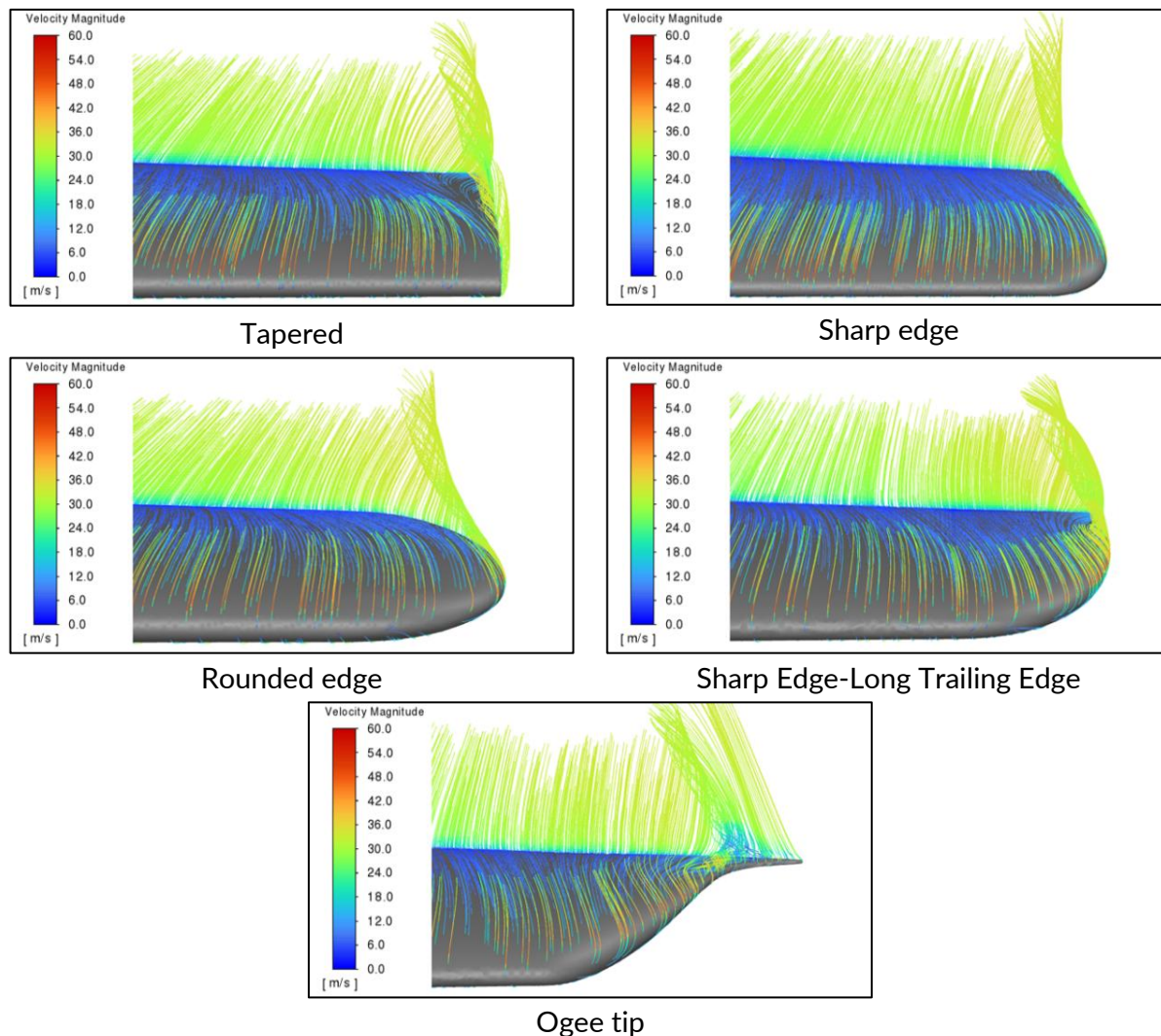
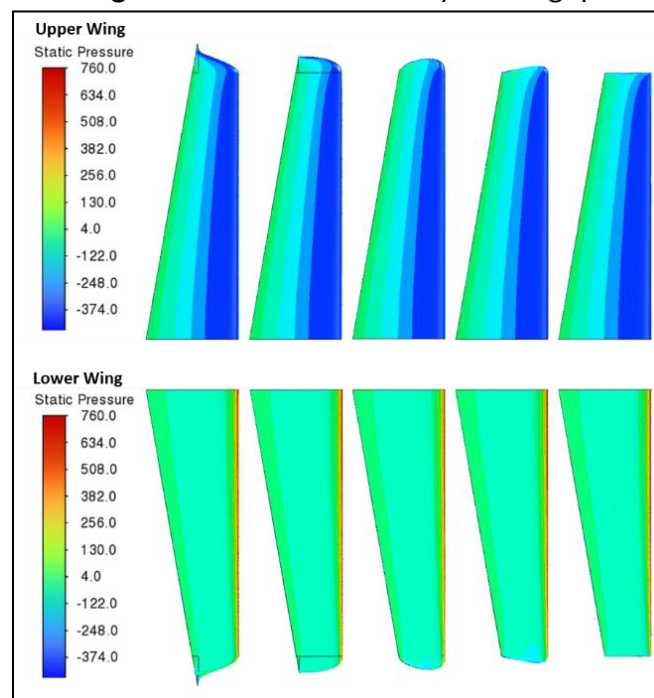


Figure 9 shows that on the upper surface of the wing, most regions are dominated by relatively low static pressure. This low-pressure region caused by the acceleration of airflow that contributes to lift generation. Variations in the colour distribution along the span indicate that the wingtip geometry influences the pressure distribution, particularly near the tip region. Configurations with sharper tips show a more concentrated low-pressure region near the wingtip, while configurations with more rounded tips display a smoother and more gradually distributed pressure pattern. These differences indicate changes in the flow behaviour around the wingtip, which affect the formation and strength of wingtip vortices.

On the lower surface, the pressure distribution is dominated by higher static pressure compared to the upper surface. Near the leading edge, a brighter colour band ranging from yellow to red represents regions of relatively higher pressure caused by flow stagnation. Toward the trailing edge, the pressure distribution becomes more uniform and is mainly characterized by green colours, indicating a gradual pressure reduction as the flow develops along the chord. Although the general pressure distribution pattern across the five configurations appears similar, small differences in pressure intensity and distribution are visible, particularly near the wingtip region.

The observed pressure distributions reflect the typical aerodynamic behaviour of a lifting surface, where the upper surface experiences lower pressure than the lower surface, generating lift through a pressure differential. Differences in wingtip geometry influence the airflow movement around the tip region. Sharper tips tend to produce stronger pressure gradients near the wingtip, which may increase the tendency for wingtip vortex formation as high-pressure air from the lower surface moves toward the lower-pressure region on the upper surface. In contrast, more rounded tips produce a smoother pressure distribution that can reduce the pressure gradient and potentially weaken the wingtip vortex, thereby improving aerodynamic efficiency. The relatively consistent pressure distribution along the chord also indicates that the airflow remains attached to the wing surface, suggesting that no significant flow separation occurs under the simulated conditions. Overall, the results indicate that variations in wingtip geometry mainly affect the local pressure distribution near the wingtip and can influence aerodynamic characteristics such as induced drag, vortex strength, and flow stability.

Figure 9. Streamline velocity on wingtip



CONCLUSION

This study systematically evaluated the aerodynamic performance of various wingtip configurations on a tapered wing using CFD with the $k-\omega$ SST turbulence model. The results demonstrate that wingtip geometry significantly influences drag characteristics, aerodynamic efficiency, and pitching behaviour.

All configurations achieved their maximum lift coefficient at an angle of attack (AoA) of 10° , with the rounded-edge wingtip producing the highest value ($Cl = 0.125$), indicating superior capability in maintaining attached flow and reducing vortex intensity. The drag coefficient increased progressively with AoA, followed by a sharp rise beyond 10° , signalling the onset of flow separation

and pre-stall conditions. Among the tested configurations, the rounded-edge wingtip consistently exhibited lower drag at moderate AoA, reflecting improved vortex control.

The lift-to-drag ratio (Cl/Cd), which represents aerodynamic efficiency, reached its peak at $AoA = 5^\circ$ for all configurations. The rounded-edge wingtip achieved the highest efficiency ($Cl/Cd \approx 20.4$), confirming its effectiveness for UAV operations within typical cruise conditions. In terms of stability characteristics, all configurations showed a nose-down pitching moment at low to moderate AoA, transitioning to a strong nose-up tendency at higher AoA, indicating increasing instability near stall.

Flow visualization and pressure contour analysis further support these findings, showing that rounded-edge wingtips produce smoother pressure gradients, weaker vortex structures, and more uniform downwash distribution compared to sharper geometries.

Overall, the rounded-edge wingtip provides the most balanced aerodynamic performance, offering improved efficiency, delayed flow separation, and more stable flow behaviour within practical operating ranges. Therefore, this configuration is recommended for fixed-wing UAV applications that prioritize endurance, efficiency, and stable flight characteristics.

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