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Research Article

Computational fluid dynamics analysis of multi-winglets for ınduced drag reduction in subsonic, transonic, and supersonic flows at different reynolds numbers

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ABSTRACT

Subsonic, transonic, and supersonic flow regimes are all analyzed in this article using Computational Fluid Dynamics (CFD) to determine how effective multi-winglets are in reducing induced drag. Both sharp-edge and flat-edge multi-winglet arrangements, based on a rectangular wing of NACA0012 airfoil with a span of 2648.44 mm and a chord of 1000 mm, were examined. The study was performed with varying Reynolds numbers for both steady and turbulent flows.Lift coefficient (CL), drag coefficient (CD), and lift-to-drag ratio (L/D) were evaluated across winglet shapes and the bare wing to determine the best aerodynamic performance. At subsonic speeds, it was discovered that the sharp-edge winglets had a greater lift curve slope and a higher L/D ratio than the baseline wing and the flat-edge winglets. Simulations were also run to compare the performance of two winglet designs at cant angles of 10^0, 35^0, and 60^0respectively. The aerodynamic performance (as measured by CL/CD) of the sharp-edge multi-winglet configuration has been found to be superior to that of the bare wing and the wing with flat-edge winglets. These findings provide valuable insights for the design optimization of multi-winglets with induced drag reduction in various flow regimes and contribute to the advancement of aerodynamic knowledge for winglet applications in aerospace engineering.

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INTRODUCTION

Winglets are small vertical extensions at the tips of aircraft wingsrepresenting a critical innovation in aircraft design, offering tangible benefits in terms of efficiency, performance, and environmental impact. Their widespread adoption across various types of aircraft underscores their significance in shaping the future of aviation.A winglet is an aerodynamic device installed on an aircraft wing to mitigate the negative effects of wingtip vortices on lift and fuel economy [1]. The ends of the wings normally extend vertically or at an angle. The lift-to-drag ratio of a wing may

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be improved with the use of winglets by decreasing the drag caused by lift and increasing the lift generated by the wing. Adding winglets raises the wing effective aspect ratio, increasing the load and stress on the structure without jeopardizing its integrity [2-3].In the mid-1970s, Richard Whitcomb was an early innovator in the study of winglet technology for use in commercial aircraft. Winglets may give gains in efficiency of more than 7% in full-size aircraft, as was discovered in flight testing of a KC-135A aircraft in 1979 and 1980 [2]. This results in savings of millions of dollars each year in fuel costs for airlines. The wingtip vortex is an inevitable byproduct of lift production in a limited wing and the source of induced drag. Research on the effects of wingtip modifications or wingtip devices on reducing induced drag has been substantial, with the goal of recommending new designs and methods that improve aerodynamic efficiency and performance.

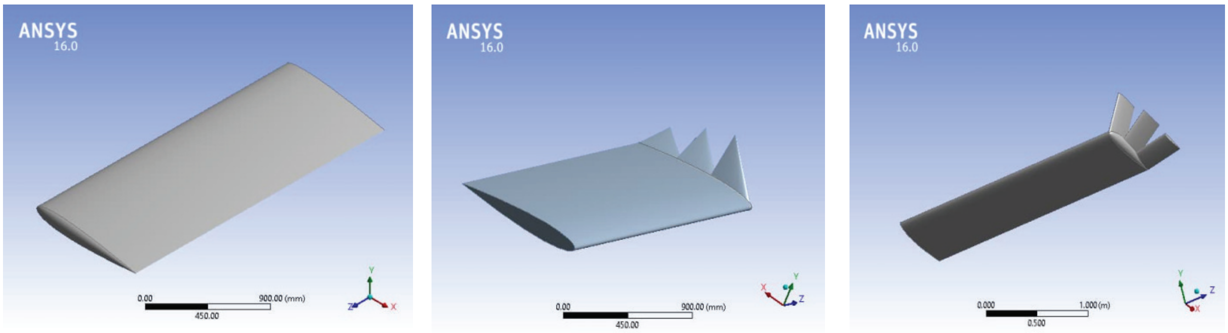
Changes to the wingtip may either weaken the vortices or reroute them away from the longitudinal axis [4]. Utilizing the energy of the whirling airflow at the wingtips, devices like winglets [5], tip-sails [6-8], and multi-winglets [9] provide extra traction, significantly increasing efficiency. For instance, Whitcomb [5] showed that winglets might decrease generated drag by 20% and boost wing efficiency by up to 9%. Reducing the duration between takeoffs and landings at major airports requires technologies that can split up the vortices into smaller, less intense sections, so easing their dispersal [10-13].Winglets provide the greatest aerodynamic advantages up to Mach 1.0, according to a comparison of wingtip devices [6], but they may cause structural issues owing to greater bending forces at the wing root. However, tip-sails achieve the same decrease in drag under low lift situations with much smaller bending moments at the wing root.Despite their already high aspect ratio wings, sailplanes have been the primary focus of wingtip device development in general aviation. The research and development of winglets for sailplanes, including the testing of scale models in wind tunnels, is mentioned by Smith and Komerath [9]. As an additional significant usage, wingtip devices are installed on agricultural aircraft to aid in the dispersion of pulverized fluid. Coimbra [8] did extensive research in this area, comparing and analyzing the impact of different wingtip devices on pulverization.

Business jets, the Boeing 747-400, commercial airlines, and military transport planes are only few examples of the types of contemporary transport aircraft that often incorporate winglets. Pennsylvania State University (PSU) [14] conducted early research on the wingtip sail, one of the first kinds of winglets. Tested in low-speed, low-turbulence wind tunnels at Reynolds numbers ranging from 0.24106 to 1.0106, the 94-097 airfoil was developed for use on high-performance sailplane winglets. Two widely used computer algorithms were used to compare their findings to the wind tunnel measurements, and both were found to be in excellent agreement with the experimental data.Methods for creating and optimizing winglet shape for Unmanned Aerial Vehicles (UAVs) were studied at Reynolds numbers close to 106 [15], leading to recent developments in winglet design. The developed approach was then used to enhance the functionality of preexisting UAV systems. The need of investigating effective forms for winglet design prompted this investigation. While most studies have focused on conventional winglets, others have looked at non-traditional variants. Numerous studies have been conducted on various types of winglets, including multiple winglets [16], spiroid wingtips [9,17], and blended winglets [18-19]. Winglets influence aircraft aerodynamics through either experimental or computational simulations. They examine the effects of winglets on parameters like drag and lift and discuss design considerations and implications for actual aircraft design emphasizing drag reduction [20] and lift analysis [21]. Together, these studies advance our comprehension of how winglets can optimize aircraft efficiency and performance.

However, research into the aerodynamic effects of various winglet designs is scant. The primary goal of this research is to undertake numerical analysis of baseline wings (without winglets) and winglets with sharp-edge and flat-edge geometries at Cant angles of 10^0, 35^0 and 60^0respectively. Different winglet designs will have their aerodynamic properties measured and compared, including their drag coefficient (CD), lift coefficient (CL), and lift-to-drag ratio (L/D).The present research work examines the efficiency of multi-winglets in reducing induced drag in all three flow regimes and at a variety of Reynolds numbers. This research makes use of CFD modelling to examine the efficiency and effectiveness of a wing with many winglets.This study looks at the feasibility of using multiple winglets to reduce induced drag, boost aerodynamic efficiency, and boost overall performance.The investigation explores the aerodynamic performance of multi-winglet configurations across a spectrum of flow regimes and Reynolds numbers. It aims to elucidate the potential of multi-winglets to enhance aerodynamic efficiency and reduce drag, thus addressing the pressing need for innovative solutions to optimize aircraft performance and reduce fuel consumption.The NACA 0012 airfoil has been designed in Ansys Workbench Design Modeler at 5° angle of attack and CFD simulations are performed for aerodynamic efficiency. In this research work, three types of models are used: wing without winglet, and wing with different feathered winglets (Sharp-feathered winglets, Cut-off-feathered winglets). Three different Cant angles were considered to find aerodynamic efficiency. The numerical analysis was carried out by considering both steady and unsteady flows in subsonic, transonic, and supersonic regimes. Vortex-Induced vibrations with natural frequency are also considered for all the wings.

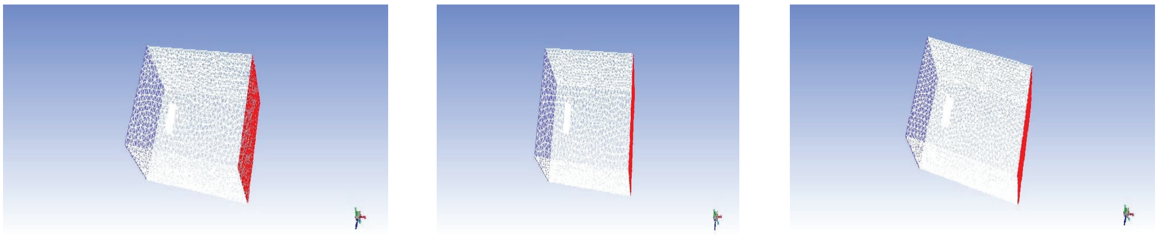
NUMERICAL CONSIDERATIONS

All the experiments were done at different Reynolds numberspertaining to subsonic, transonic, and supersonic flows in steady and unsteady in different flow velocities. Figure 1 displays the winglets designed in AnsysWorkbench.



(a) (b) (c)

Figure 1. (a) Wing without winglets (b) Wing with sharp-edge multi-winglets (c) Wing with flat-edge multi-winglets.



(a) (b) (c)

Figure 2. (a) Meshing of wing without winglets (b) Meshing of wing with sharp-edge winglets (c) Meshing of wing with sharp-edge winglets.

Afinite volume approach is employed for the present simulations. A 3D unstructured tetrahedral mesh was created to calculate the flow around the object as shown in Figure 2. The intricacy of the model necessitated the use of an unstructured mesh, which is more suitable to such intricate geometries. Unstructured meshes provide several benefits, including faster grid generation times and the flexibility to enhance computation accuracy. Smooth transition of tetrahedral meshes from the solid surface has been employed without any boundary layer inflation, smooth transition.

Once the mesh generation was completed, a numerical simulation was conducted using Spalart-Allmaras turbulence model. No slip condition was used on the solid surface. Velocity inlet condition is employed at the inlet whereas outflow condition is defined at the outlet boundary.

RESULTS AND DISCUSSION

Two models of 3D rectangular wings, one with multi-winglets like NACA0012 and the other without winglets, were compared. The authors looked at a variety of aerodynamic factors, such as the drag coefficient (CD), lift coefficient (CL), and lift-to-drag ratio (CL/CD), and streamlines, to draw their conclusions. All simulations were run using an angle of attack of 5 degrees and were run at different Mach values. The effects of the winglet design on

Table 1. Various flow parameters

Flow	Velocity (m/s)	Reynolds no (Re)	Mach no
Subsonic	100	4.06e+07	0.029
	150	6.09e+07	0.44
	200	8.12e+07	0.58
Transonic	273	1.11e+08	0.79
	275	1.12e+08	0.8
	290	1.18e+08	0.84
Supersonic	450	1.83e+08	1.31
	510	2.07e+08	1.49
	710	2.88e+08	2.1

Table 2. Recipe and polymerization conditions for preparation of the m-poly (DVBVIM) microbeads.

Table 2 (a). Lift coefficient under steady flow				**Table 2 (b).** Lift coefficient under unsteady flow			
Velocity (m/sec)	**(a)**	**(b)**	**(c)**	**Velocity (m/sec)**	**(a)**	**(b)**	**(c)**
100	4.97E-01	5.34E-01	5.29E-01	100	4.97E-01	5.33E-01	5.27E-01
150	5.18E-01	5.54E-01	5.48 E-01	150	5.18E-01	5.51E-01	5.47 E-01
200	5.56 E-01	5.87E-01	5.91 E-01	200	5.55 E-01	5.84E-01	5.87 E-01
273	6.30 E-01	6.51E-01	7.14 E-01	273	6.50 E-01	6.74E-01	7.26 E-01
275	6.63 E-01	6.78E-01	7.27 E-01	275	6.56 E-01	6.77E-01	7.37 E-01
290	6.90 E-01	7.01 E-01	7.64 E-01	290	6.19 E-01	7.39E-01	7.92 E-01
450	6.22 E-01	6.04 E-01	6.67 E-01	450	6.21 E-01	6.03 E-01	6.66 E-01
510	5.58 E-01	5.28 E-01	5.90 E-01	510	5.55 E-01	5.28 E-01	5.92 E-01
710	3.88 E-01	3.64 E-01	3.98 E-01	710	3.86 E-01	3.64 E-01	3.98 E-01

the wing aerodynamic performance were analyzed, and the findings were documented in Table 1.

Table 2 provides a comparison of the lift coefficient (CL) of the different models, including winglets and bare wing, at a fixed angle of attack (α) of 5°, at various velocities across different flow regimes. The analysis considered both steady and unsteady flow conditions. The results reveal the impact of the winglet design on the lift coefficient of the wing, and how it performs under varying flow conditions. In Table 2, columns (a), (b) and (c) are used for wings without winglets, wings with sharp-edge multi-winglets and wings with flat-edge multi-winglets respectively.

Figure 3(a) and 3(b) show that the lift coefficient (CL) is greatest for the flat-edge multi-winglet design, followed by the sharp-edge multi-winglet arrangement, and finally the bare wing. This trend is observed in both steady and unsteady flow conditions, at varying velocities. Thus, the higher CL values obtained in the simulations show that the adoption of flat-edge multi-winglets may increase the overall lift performance of the wing in comparison to alternative configurations.

Figure 4(a) and 4(b) show that compared to the sharp-edge multi-winglet design and the bare wing, the flat-edge multi-winglet configuration has the largest drag coefficient (CD). This pattern holds true across a range of flow velocities and in both steady and unstable circumstances. Therefore, although the use of flat-edge multi-winglets might enhance the wing's lift performance, it may incur greater drag values as a result. For this reason, the balance between lift and drag must be taken into account while constructing winglet arrangements.

Analysis of Lift Coefficient (CD)

At an angle of attack of 5 degrees, Table 3 shows the variation of drag coefficient CD with velocity throughout many flow regimes: with and without winglets. Columns

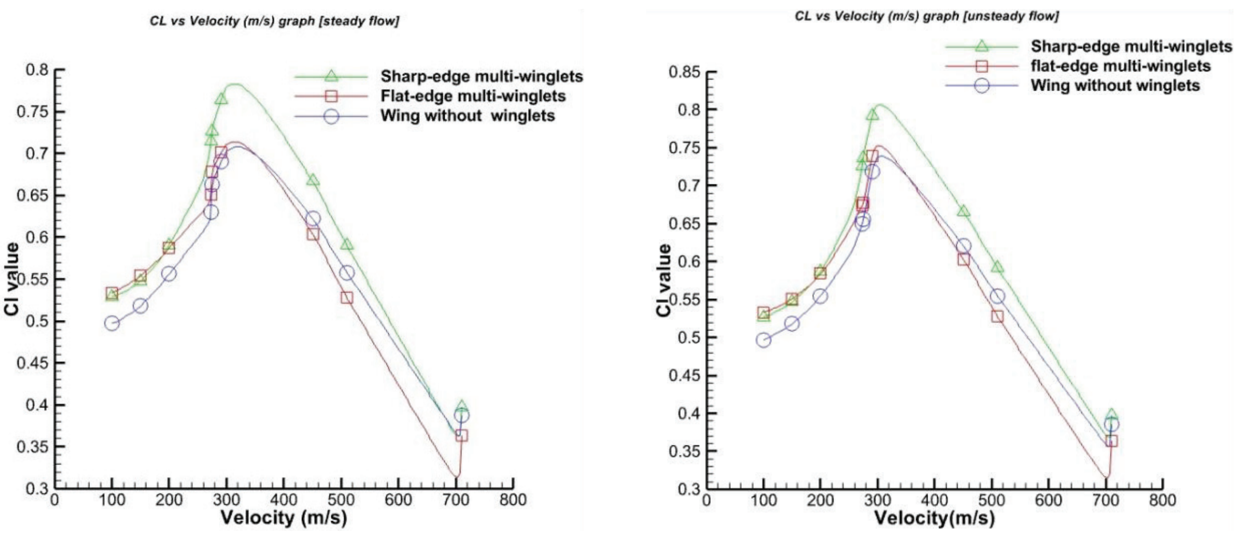


Figure 3. (a) Cl vs velocity variation understeady flow (b) Cl vs velocity variation under unsteady flow

Table 3. Drag coefficient, CD comparison in steady and unsteady flow

Table 3(a). Steady flow CD				**Table 3(b).** Unsteady flow CD			
Velocity (m/sec)	**(a)**	**(b)**	**(c)**	**Velocity (m/sec)**	**(a)**	**(b)**	**(c)**
100	5.66E-02	5.89E-02	7.61E-02	100	5.58E-02	5.87E-02	7.57E-02
150	5.59E-02	5.91E-02	7.61 E-02	150	5.60E-02	5.75E-02	7.64 E-02
200	5.77 E-02	6.15E-02	7.7 1E-02	200	5.76 E-02	6.16E-02	7.84E-02
273	1.17 E-01	1.21E-01	1.58 E-01	273	1.27 E-01	1.30E-01	1.61E-01
275	1.32 E-01	1.30E-01	1.59 E-01	275	1.31 E-01	1.33E-01	1.66 E-01
290	1.55 E-01	1.55E-01	2.01 E-01	290	1.74 E-01	1.72E-01	2.11 E-01
450	3.38 E-01	3.21E-01	3.58 E-01	450	3.38 E-01	3.22E-01	3.58 E-01
510	3.29 E-01	3.12 E-01	3.48 E-01	510	3.30 E-01	3.12 E-01	3.48 E-01
710	2.99 E-01	2.81 E-01	3.16 E-01	710	2.79 E-01	2.81 E-01	3.16 E-01

(a), (b) and (c) are used for wings without winglets, wings with sharp-edge multi-winglets and wings with flat-edge multi-winglets respectively.

Analysis of Lift Coefficient (CL/CD)

Table 4 compares the lift-to-drag ratio (CL/CD) at a fixed angle of attack of 5° and varying velocities across different flow regimes for the various winglet shapes and the bare wing. The analysis considers both steady and unsteady flow conditions. The results illustrate how the winglet design influences the wing's lift-to-drag ratio and how it fares in different flow regimes. Because it measures how well the wing creates lift while minimizing drag, the lift-to-drag ratio is a crucial metric to consider when designing wings. Table 4 provides valuable insights into the aerodynamic performance of the different winglet configurations, which can be used to optimize the design of future winglet systems.Columns (a), (b) and (c) are used for wings without winglets, wings with sharp-edge multi-winglets and wings with flat-edge multi-winglets respectively.

Figure 5(a) and 5(b) display the results of the tests, showing that the multi-winglet design with sharp edges has the greatest Lift-to-Drag ratio (CL/CD) compared to the flat-edge multi-winglet configuration and the bare wing configuration. This holds true for both steady and unsteady flow conditions at varying velocities. Specifically, the sharp-edge multi-winglet configuration achieved the highest CL/CD, followed by the bare wing configuration which had the second highest CL/CD.

Study of Streamlines

This study provides a visual representation of the streamline flow over the studied wing equipped with winglets and the bare wing at various velocities and a fixed angle of attack

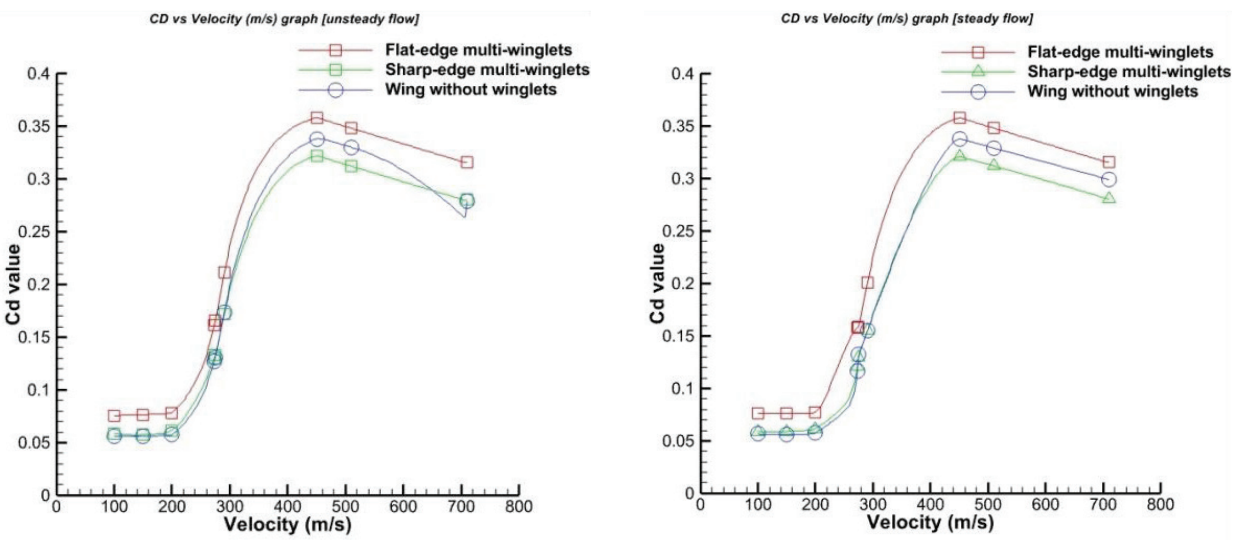


Figure 4 (a). Cd vs velocity (steady flow) (b) Cd vs velocity (unsteady flow)

Table 4. Ratio of CL and CD

Table 4(a). Steady Flow Cl/Cd				**Table 4(b).** Unsteady Flow Cl/Cd			
Velocity (m/sec)	**(a)**	**(b)**	**(c)**	**Velocity (m/sec)**	**(a)**	**(b)**	**(c)**
100	5.58E-02	5.87E-02	7.57E-02	100	5.66E-02	5.89E-02	7.61E-02
150	5.60E-02	5.75E-02	7.64 E-02	150	5.59E-02	5.91E-02	7.61 E-02
200	5.76 E-02	6.16E-02	7.84E-02	200	5.77 E-02	6.15E-02	7.7 1E-02
273	1.27E-01	1.30E-01	1.61 E-01	273	1.17 E-01	1.21E-01	1.58 E-01
275	1.31 E-01	1.33E-01	1.66 E-01	275	1.32 E-01	1.30E-01	1.59 E-01
290	1.74 E-01	1.72E-01	2.11 E-01	290	1.55 E-01	1.55E-01	2.01 E-01
450	3.38 E-01	3.22E-01	3.58 E-01	450	3.38 E-01	3.21E-01	3.58 E-01
510	3.30 E-01	3.12 E-01	3.48 E-01	510	3.29 E-01	3.12 E-01	3.48 E-01
710	2.79 E-01	2.81 E-01	3.16 E-01	710	2.99 E-01	2.81 E-01	3.16 E-01

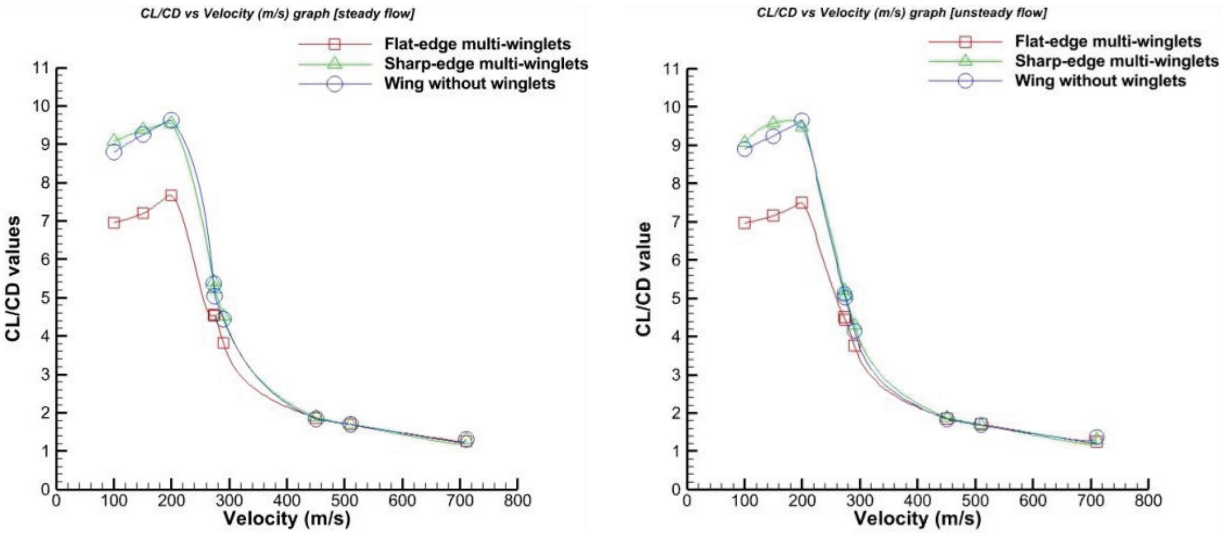
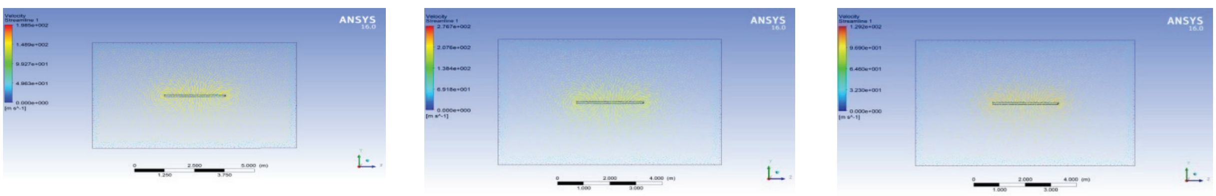


Figure 5. (a) CL/CD vs velocity max graph (steady flow) b) CL/CD vs velocity max graph (unsteady flow)

of 5 degrees. The focus of these streamlines is on the wingtip region where trailing vortices are known to occur. Notably, these trailing vortices are most prominent when an airplane is taking off at the maximum angle of attack.

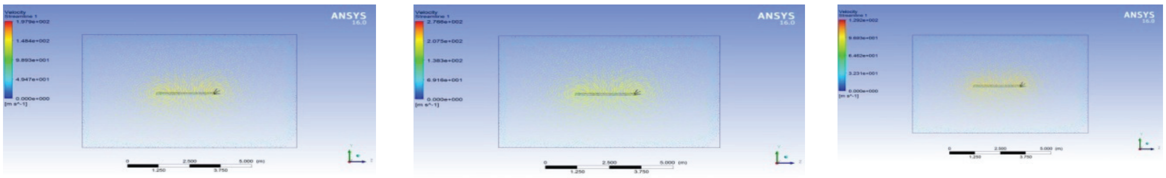
Steady Flow

The wing without winglets performs efficiently across different velocities under steady subsonic flow conditions. At 100 m/s, it achieves a high lift-to-drag ratio of 8.79, indicating effective lift generation with minimal drag. As the velocity increases to 150 m/s, the lift-to-drag ratio improves slightly to 9.25, showcasing continued efficient aerodynamic performance. At 200 m/s, while still efficient, there's a slight reduction in the lift-to-drag ratio to 6.63, suggesting a proportionate increase in drag relative to lift. Overall, the



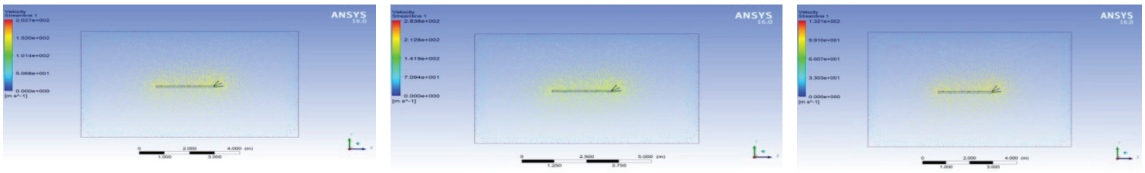
(a) at 100 m/s (b) at 150 m/s (c) at 200 m/s

Figure 6. Wing without winglets under steady subsonic flow.



(a) at 100 m/s (b) at 150 m/s (c) at 200 m/s

Figure 7. Wing with sharp-edge multi-wingletsunder subsonic flow



(a) at 100 m/s (b) at 150 m/s (c) at 200 m/s

Figure 8. Wing with flat-edge multi-wingletsunder subsonic flow.

wing demonstrates consistent and effective aerodynamic characteristics across the tested velocities.

At 100 m/s: The lift coefficient is 0.529, with a corresponding drag coefficient of 0.0761, resulting in a lift-to-drag ratio of 6.96.At 150 m/s: The lift coefficient slightly increases to 0.548, maintaining the same drag coefficient, resulting in a lift-to-drag ratio of 7.20.At 200 m/s: Further improvement is observed, with the lift coefficient increasing to 0.591 and the drag coefficient decreasing to 0.0571, resulting in an enhanced lift-to-drag ratio of 7.67.

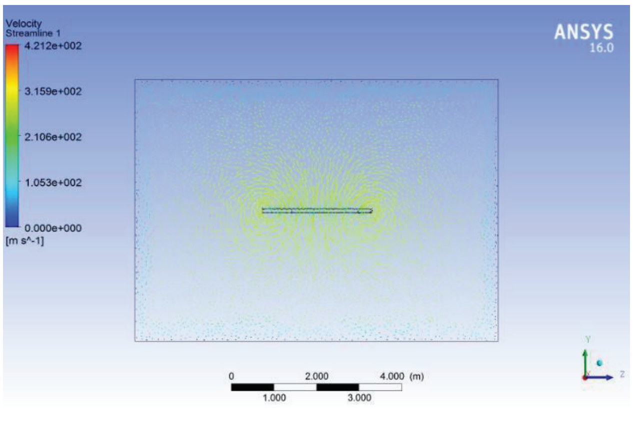
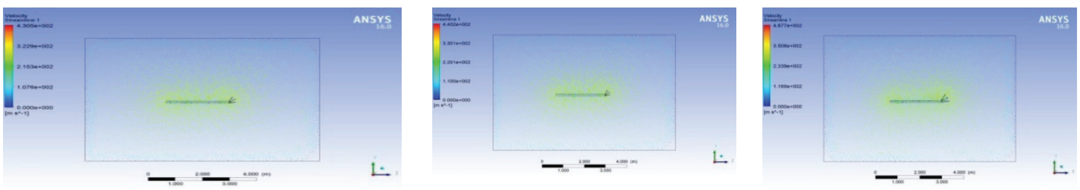


Figure 9. Wing without winglets under transonic flowat 273 m/s

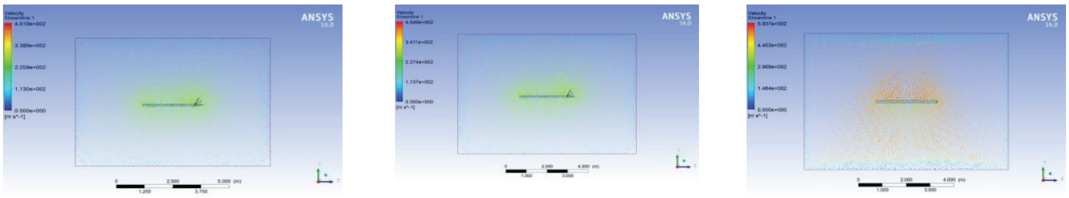
The wing with sharp-edge multi-winglets performs effectively across different velocities under subsonic flow conditions. At 100 m/s, it achieves a lift-to-drag ratio of 9.07, indicating efficient lift generation with minimal drag. As the velocity increases to 150 m/s, the lift-to-drag ratio improves slightly to 9.37, maintaining efficient aerodynamic performance. At 200 m/s, the lift-to-drag ratio further increases to 9.54, demonstrating continued effectiveness in lift generation relative to drag. Overall, the wing with sharp-edge multi-winglets exhibits consistent and efficient aerodynamic characteristics across the tested velocities.

Under transonic flow conditions, At 273 m/s: The lift coefficient is 0.630, with a corresponding drag coefficient of 0.117, resulting in a lift-to-drag ratio of 5.37.At 275 m/s: A slight increase in lift coefficient to 0.663 is observed, accompanied by a higher drag coefficient of 0.132, resulting in a slightly lower lift-to-drag ratio of 5.04.At 290 m/s: Further increase in lift coefficient to 0.690 is observed,



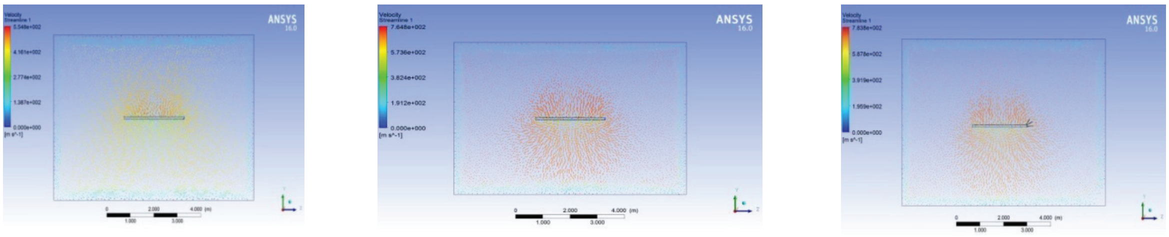
(a) at 273 m/s (b) at 275 m/s (c) at 290 m/s

Figure 10. Wing with sharp-edge multi-winglets under transonic flow.



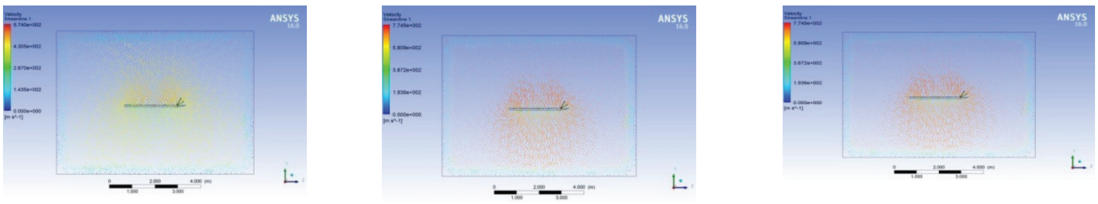
(a) at 273 m/s (b) at 275 m/s (c) at 290 m/s

Figure 11. Wing with flat-edge multi-wingletsunder transonic flow.



(a) at 450 m/s (b) at 510 m/s (c) at 710 m/s

Figure 12. Wing without wingletsunder supersonic flow.



(a) at 450 m/s (b) at 510 m/s (c) at 710 m/s

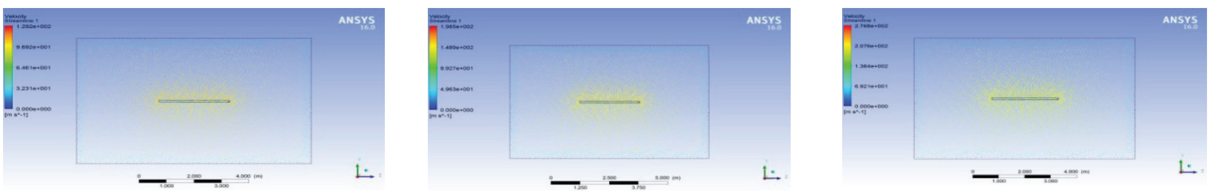
Figure 13. Wing with sharp-edge multi-winglets under supersonic flow.

with an increased drag coefficient of 0.155, resulting in a reduced lift-to-drag ratio of 4.44.

At 273 m/s: The lift coefficient is 0.651, accompanied by a drag coefficient of 0.121, resulting in a lift-to-drag ratio of 5.40.At 275 m/s: There is a slight increase in the lift coefficient to 0.678, with a corresponding drag coefficient of 0.130, resulting in a slightly lower lift-to-drag ratio of 5.22. At 290 m/s: The lift coefficient further increases to 0.701, with an increased drag coefficient of 0.155, resulting in a reduced lift-to-drag ratio of 4.52.

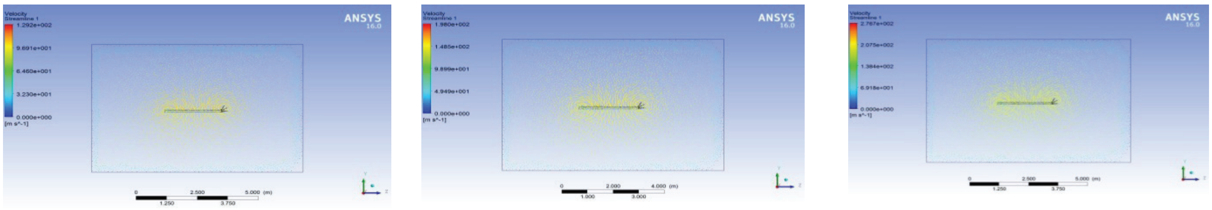
At 450 m/s: The lift coefficient is 0.604, with a corresponding drag coefficient of 0.321, resulting in a lift-to-drag ratio of 1.88.At 510 m/s: The lift coefficient decreases to 0.528, while the drag coefficient decreases slightly to 0.312, resulting in a lift-to-drag ratio of 1.69.At 710 m/s: Both the lift coefficient and drag coefficient decrease further to 0.364 and 0.281 respectively, resulting in a reduced lift-to-drag ratio of 1.29.

At 450 m/s: The lift coefficient is 0.604, with a corresponding drag coefficient of 0.321, resulting in a lift-to-drag ratio of 1.88.At 510 m/s: The lift coefficient decreases



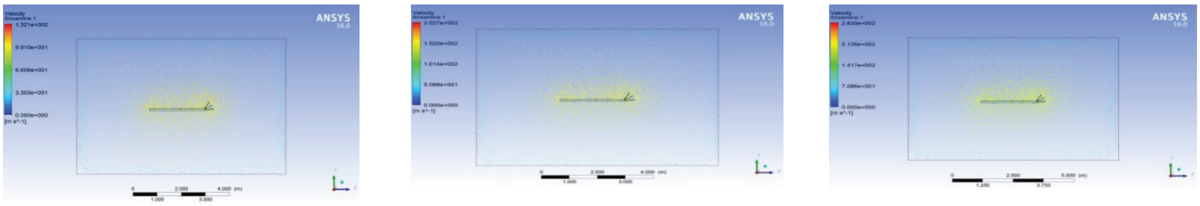
(a) at 100 m/s (b) at 150 m/s (c) at 200 m/s

Figure 14. Wing without winglets under unsteady subsonic flow.



(a) at 100 m/s (b) at 150 m/s (c) at 200 m/s

Figure 15. Wing with sharp-edge multi-winglets under unsteady subsonic flow.



(a) at 100 m/s (b) at 150 m/s (c) at 200 m/s

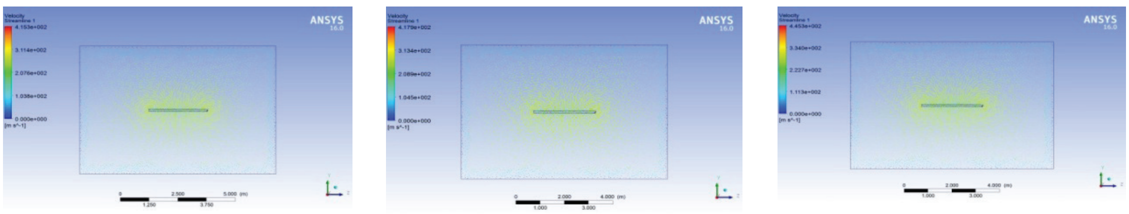
Figure 16. Wing with flat-edge multi-wingletsunder unsteady subsonic flow.

to 0.528, while the drag coefficient decreases slightly to 0.312, resulting in a lift-to-drag ratio of 1.69.At 710 m/s: Both the lift coefficient and drag coefficient decrease further to 0.364 and 0.281 respectively, resulting in a reduced lift-to-drag ratio of 1.29.

Unsteady Flow

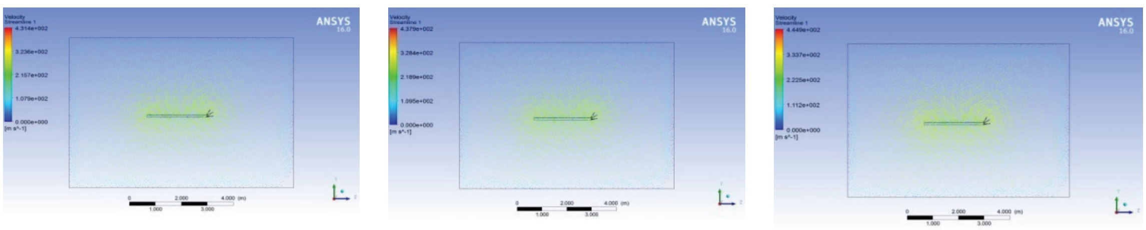
At 100 m/s, the lift coefficient (Cl) is approximately 0.497, and the drag coefficient (Cd) is about 0.0568, resulting in a lift-to-drag ratio (Cl/Cd) of around 8.79.At 150 m/s, both Cl and Cd increase, leading to an improved Cl/Cd ratio of approximately 9.25.At 200 m/s, Cl increases further to about 0.555, but Cd also increases slightly to approximately 0.0576, resulting in a lower Cl/Cd ratio of about 6.64.

At 100 m/s**:** The lift coefficient (Cl) is approximately 0.533, and the drag coefficient (Cd) is about 0.0587, resulting in a lift-to-drag ratio (Cl/Cd) of around 9.07.At 150



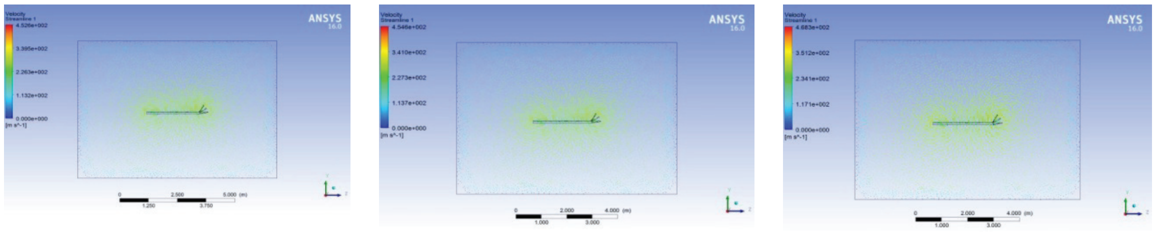
(a) at 273 m/s (b) at 275 m/s (c) at 290 m/s

Figure 17. Wing without wingletsunder unsteady transonic flow.



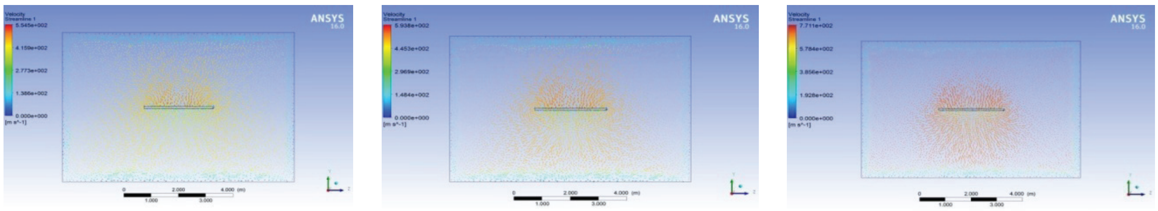
(a) at 273 m/s (b) at 275 m/s (c) at 290 m/s

Figure 18. Wing with sharp-edge multi-wingletsunder unsteady transonic flow.



(a) at 273 m/s (b) at 275 m/s (c) at 290 m/s

Figure 19. Wing with flat-edge multi-wingletsunder unsteady transonic flow.



(a) at 450 m/s (b) at 510 m/s (c) at 710 m/s

Figure 20. Wing without wingletsunder unsteady supersonic flow

m/s: Both Cl and Cd increase, with Cl reaching approximately 0.551 and Cd approximately 0.0575. This leads to an improved Cl/Cd ratio of approximately 9.58. At 200 m/s: Cl increases further to about 0.584, but Cd also increases slightly to approximately 0.0516. Consequently, the Cl/Cd ratio decreases to about 9.47.

At 100 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.527 and a drag coefficient (Cd) of about 0.0757, resulting in a lift-to-drag ratio (Cl/Cd) of around 6.97.At 150 m/s: Both Cl and Cd increase, with Cl reaching approximately 0.547 and Cd approximately 0.0764. This leads to an improved Cl/Cd ratio of approximately 7.16.At 200 m/s: Cl increases further to about 0.587, but Cd also increases slightly to approximately 0.0784. Consequently, the Cl/Cd ratio increases to about 7.49.

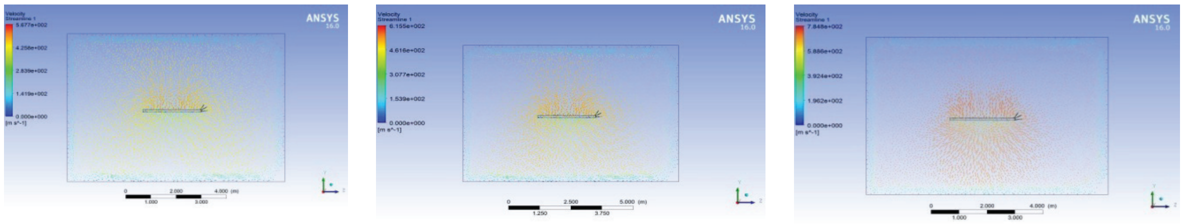
At 273 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.65 and a drag coefficient (Cd) of about 0.127, resulting in a lift-to-drag ratio (Cl/Cd) of around 5.12**.**At 275 m/s: Both Cl and Cd increase, with Cl reaching approximately 0.656 and Cd approximately 0.131. This leads to a slightly lower lift-to-drag ratio of approximately 5.01 compared to the previous velocity.At 290 m/s: Cl increases further to about 0.719, but Cd also increases significantly to approximately 0.174. Consequently, the lift-to-drag ratio decreases to about 4.14.

At 273 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.674 and a drag coefficient (Cd) of about 0.13, resulting in a lift-to-drag ratio (Cl/Cd) of around 5.20.At 275 m/s: Both Cl and Cd increase, with Cl reaching approximately 0.677 and Cd approximately 0.133. This leads to a slightly lower lift-to-drag ratio of approximately 5.07 compared to the previous velocity.At 290 m/s: Cl decreases slightly to about 0.639, while Cd increases significantly to approximately 0.172. Consequently, the lift-to-drag ratio decreases to about 4.30.

At 273 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.726 and a drag coefficient (Cd) of about 0.161, resulting in a lift-to-drag ratio (Cl/Cd) of around 4.50.At 275 m/s: Both Cl and Cd increase, with Cl reaching approximately 0.737 and Cd approximately 0.166. This leads to a slightly lower lift-to-drag ratio of approximately 4.44 compared to the previous velocity.At 290 m/s: Cl increases further to about 0.792, while Cd also increases significantly to approximately 0.211. Consequently, the lift-to-drag ratio decreases to about 3.75.

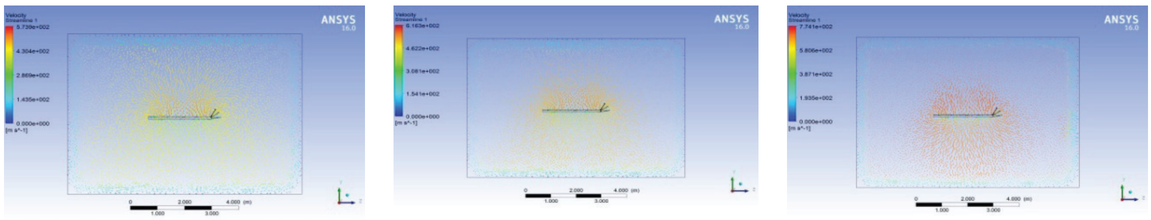
At 450 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.621 and a drag coefficient (Cd) of about 0.338, resulting in a lift-to-drag ratio (Cl/Cd) of around 1.84.At 510 m/s: Both Cl and Cd decrease, with Cl reaching approximately 0.555 and Cd approximately 0.330. This leads to a slightly lower lift-to-drag ratio of approximately 1.68 compared to the previous velocity.At 710 m/s: Cl decreases further to about 0.386, while Cd also decreases to approximately 0.279. Consequently, the lift-to-drag ratio decreases to about 1.38.

At 450 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.603 and a drag coefficient (Cd) of about 0.322, resulting in a lift-to-drag ratio (Cl/Cd) of around 1.88.At 510 m/s: Both Cl and Cd decrease, with Cl reaching approximately 0.528 and Cd approximately 0.312. This leads to a slightly lower lift-to-drag ratio of approximately 1.69 compared to the previous velocity.At 710 m/s: Cl decreases further to about 0.364, while Cd also decreases



(a) at 450 m/s (b) at 510 m/s (c) at 710 m/s

Figure 21. Wing with sharp-edge multi-winglets under unsteady supersonic flow.



(a) at 450 m/s (b) at 510 m/s (c) at 710 m/s

Figure 22. Wing with flat-edge multi-wingletsunder unsteady supersonic flow.

to approximately 0.281. Consequently, the lift-to-drag ratio decreases to about 1.29.

At 450 m/s: The wing achieves a lift coefficient (Cl) of approximately 0.666 and a drag coefficient (Cd) of about 0.358, resulting in a lift-to-drag ratio (Cl/Cd) of around 1.86.At 510 m/s: Both Cl and Cd decrease, with Cl reaching approximately 0.592 and Cd approximately 0.348. This leads to a slightly lower lift-to-drag ratio of approximately 1.70 compared to the previous velocity.At 710 m/s: Cl decreases further to about 0.398, while Cd also decreases to approximately 0.316. Consequently, the lift-to-drag ratio decreases to about 1.26.

Results and Discussions of Steady and Unsteady Flows

Analysis revealed that wings with sharp edge multiple winglets exhibited superior aerodynamic efficiency compared to other configurations across all flow velocities. Notably, at a velocity of 150m/s, sharp edge winglets demonstrated the highest CL/CD values, indicating their effectiveness in improving aerodynamic performance. The results highlight the significance of considering winglet design in enhancing overall aerodynamic efficiency, particularly in unsteady flow conditions.

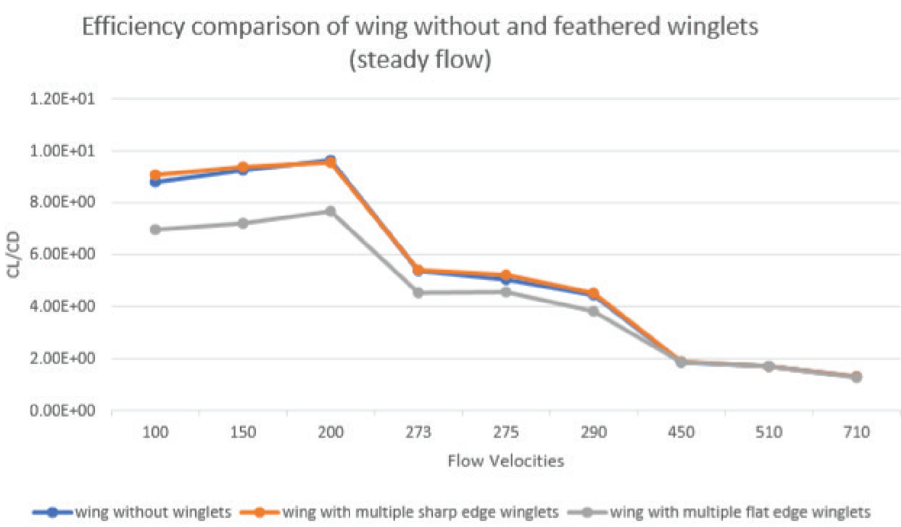


Figure 23. Comparison of wing with Feathered winglets and wing without winglets in steady flow.

Table 5. Flow Comparison table of wing without winglets in steady flow

Wing without winglets				
Flow	**velocity**	**Cl**	**Cd**	**Cl/cd**
Subsonic	100	4.97E-01	5.66 E-02	8.79 E+00
	150	5.18 E-01	5.59 E-02	9.25 E+00
	200	5.56 E-01	5.77 E-02	6.63 E+00
Transonic	273	6.30 E-01	1.17 E-01	5.37 E+00
	275	6.63 E-01	1.32 E-01	5.04 E+00
	290	6.90 E-01	1.55 E-01	4.44 E+00
Supersonic	450	6.22 E-01	3.38 E-01	1.84 E+00
	510	5.58 E-01	3.29 E-01	1.69 E+00
	710	3.88 E-01	2.99 E-01	1.30 E+00

Table 6. Flow Comparison table of wing Multiple sharp edge winglets in steady flow

Wing without winglets				
Flow	**velocity**	**Cl**	**Cd**	**Cl/cd**
Subsonic	100	5.34E-01	5.89 E-02	9.07E+00
	150	5.54 E-01	5.91 E-02	9.37 E+00
	200	5.87 E-01	6.15 E-02	9.54 E+00
Transonic	273	6.51 E-01	1.21 E-01	5.40 E+00
	275	6.78 E-01	1.30 E-01	5.22 E+00
	290	7.01 E-01	1.55 E-01	4.52 E+00
Supersonic	450	6.04 E-01	3.21 E-01	1.88 E+00
	510	5.28 E-01	3.12 E-01	1.69 E+00
	710	3.64 E-01	2.81E-01	1.29E+00

Table 7. Flow comparison table of wing multiple sharp edge winglets in steady flow

Wing with winglets				
Flow	**velocity**	**Cl**	**Cd**	**Cl/cd**
Subsonic	100	5.29E-01	7.61 E-02	6.96 E+00
	150	5.48 E-01	7.61 E-02	7.20E+00
	200	5.91 E-01	5.71 E-02	7.67 E+00
Transonic	273	7.14 E-01	1.58 E-01	4.53 E+00
	275	7.27 E-01	1.59 E-01	4.56 E+00
	290	7.64 E-01	2.01 E-01	3.81 E+00
Supersonic	450	6.67 E-01	3.58 E-01	1.86 E+00
	510	5.90E-01	3.48 E-01	1.70 E+00
	710	3.98 E-01	3.16 E-01	1.26 E+00

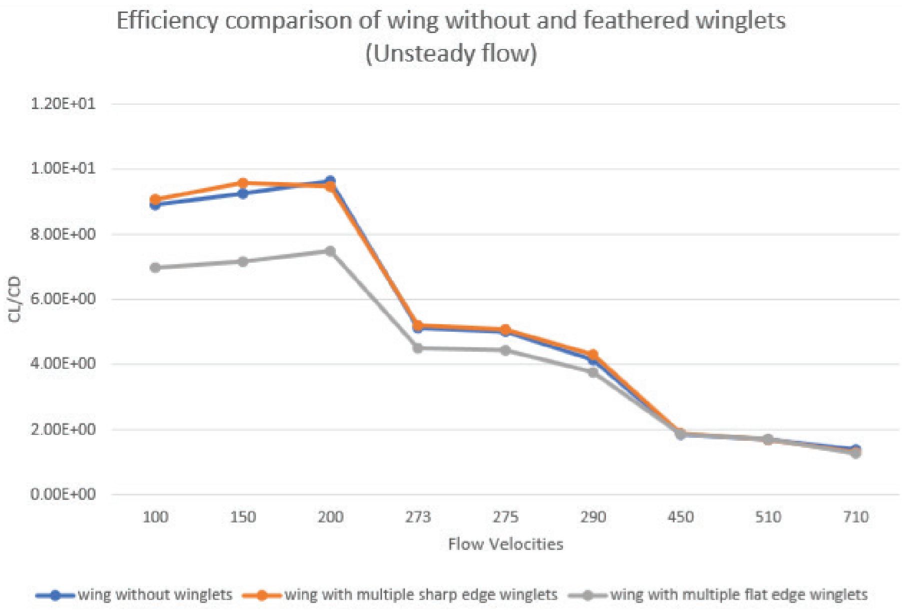


Figure 24. Comparison of wing with Feathered winglets and wing without winglets in unsteady flow.

Table 8. Flow comparison table of wing without winglets in unsteady flow

Wing without winglets				
flow	**velocity**	**Cl**	**Cd**	**Cl/cd**
subsonic	100	4.97E-01	5.68 E-02	8.79 E+00
	150	5.18 E-01	5.60 E-02	9.25 E+00
	200	5.55E-01	5.76 E-02	6.64 E+00
Transonic	273	6.50 E-01	1.27 E-01	5.12 E+00
	275	6.56 E-01	1.31 E-01	5.01 E+00
	290	7.19 E-01	1.74 E-01	4.14 E+00
supersonic	450	6.21 E-01	3.38 E-01	1.84 E+00
	510	5.55 E-01	3.30 E-01	1.68 E+00
	710	3.86 E-01	2.79 E-01	1.38 E+00

Table 9. Flow comparison table of wing multiple sharp edge winglets in unsteady flow

Wing without winglets				
flow	**velocity**	**Cl**	**Cd**	**Cl/cd**
subsonic	100	5.33E-01	5.87 E-02	9.07 E+00
	150	5.51 E-01	5.75 E-02	9.58 E+00
	200	5.84 E-01	5.16 E-02	9.47 E+00
Transonic	273	6.74 E-01	1.30 E-01	5.20 E+00
	275	6.77 E-01	1.33 E-01	5.07 E+00
	290	6.39 E-01	1.72 E-01	4.30 E+00
supersonic	450	6.03 E-01	3.22 E-01	1.88 E+00
	510	5.28 E-01	3.12 E-01	1.69 E+00
	710	3.64 E-01	2.81 E-01	1.29 E+00

Table 10. Flow comparison table of wing multiple flat edge winglets in unsteady flow

Wing without winglets				
flow	**velocity**	**Cl**	**Cd**	**Cl/cd**
subsonic	100	5.27E-01	7.57 E-02	6.97 E+00
	150	5.47E-01	7.64 E-02	7.16 E+00
	200	5.87E-01	7.84 E-02	7.49 E+00
Transonic	273	7.26E-01	1.61 E-01	4.50 E+00
	275	7.37E-01	1.66 E-01	4.44 E+00
	290	7.92E-01	2.11 E-01	3.75 E+00
supersonic	450	6.66E-01	3.58 E-01	1.86 E+00
	510	5.92E-01	3.48 E-01	1.70 E+00
	710	3.98E-01	3.16 E-01	1.26 E+00

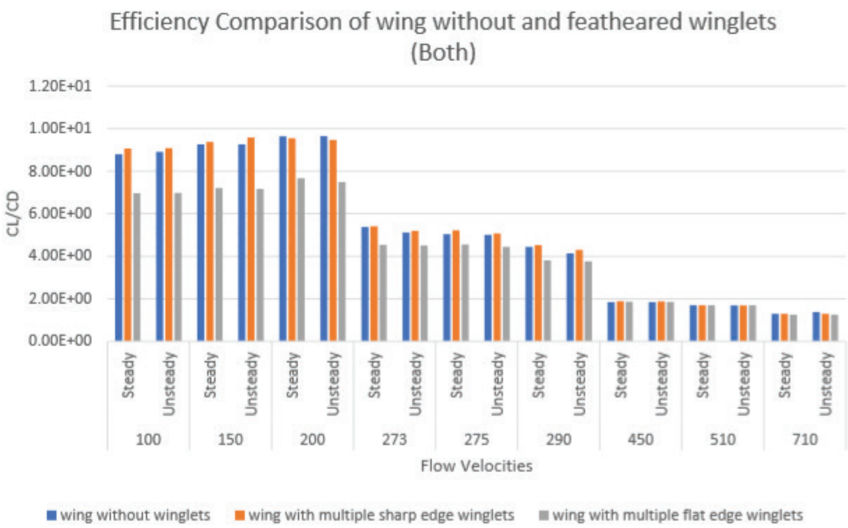


Figure 25. Efficiency comparison of steady and unsteady flow of wing without and wing with feathered winglets.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

CONCLUSION

The objective of this project is to propose alternative designs for winglets that surpass the conventional designs, leading to improved aircraft performance and reduced fuel consumption. To save time and money, the winglets' performance is predicted using Computational Fluid Dynamics (CFD) before they are tested in a wind tunnel. The time needed to make adjustments and arrive at the best design is reduced at this stage. There are, however, downsides to winglets that must be dealt with, such as the increased bending moment at the wing root, which might need extra structural reinforcing, as well as the increased expense and complexity of construction, and the alteration of handling and stability characteristics. Sometimes the resultant drag decrease is cancelled out by the winglet's viscous drag. Therefore, winglets need careful design to counteract these and other issues.

The study demonstrates the potential improvements that can be achieved with the use of multi-winglets in controlling wingtip vortices. Results from the CFD analysis showed a notable improvement in performance metrics, including advances in aerodynamic efficiency and improvements while retaining the important components of the baseline wing. The use of winglets did not appreciably affect the structural loading owing to lift, hence there were no detrimental structural repercussions.Results show that at a 5° angle of attack, the efficiency of multi-winglets drops significantly at higher Reynolds numbers. Separation areas near the winglet's root led to a rise in CD for low CL circumstances, and the local flow incidence angle was substantially negative. At low CL, the drag caused by root separation is greater than the thrust created by the winglet, a problem shared not just by multi-winglets but also by single winglets. The importance of these gaps increases as the Reynolds number drops.

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