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Science Article

Investigating the Effect of Different Winglet Cant Angles on a Supercritical Wing Aerodynamic Efficiency at Lower Reynolds numbers

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This study focuses on improving performance of a supercritical wing equipped with winglets at different cant angles. This study aims to experimentally investigate the variation of aerodynamic performance of a supercritical wing of NASA Sc (2)-0410 airfoil at lower Reynolds numbers with winglets at various cant angles. The tests were performed by measuring the lift and drag force using a three-component balance within a broad range of angle of attack from -4 to 20 degrees and at three different subsonic flow velocities. Results include changes in lift, drag, and aerodynamic performance for each winglet cant angle compared to the baseline wing. The results show that winglets generally increase the lift force and decrease the drag force by decreasing the size and strength of the wingtip vortices. Moreover, the optimal winglet for each case is extracted based on the aerodynamic performance provided by each winglet. In order to better and more accurately compare the effect of different mounting angles of the winglet on the aerodynamic performance of the base wing, the impact of each winglet is shown separately. Accordingly, it is observed that the winglets with angles of 0^o and 15^o, namely W0 and W15, have shown good performance in increasing the lift coefficient. Also, the winglet with 90 degrees has shown good performance in creating the least drag force.

Keywords: *Experimental Aerodynamics, Wing Tip Vortex, Supercritical Wing, Winglet, Aerodynamic Coefficients*

Introduction

Environmental factors and operating costs have led the industry to find ways to increase the efficiency of commercial air transportation, which in turn has led to the emergence of innovative methods to reduce induced drag or increase lift. One of these methods is the use of a winglet. [1] Winglets were first introduced and developed in the late eighteenth century by the British engineer Frederick Lanchester. He believed that a vertical surface at the wingtip could reduce drag after controlling wingtip vortices. [2] Winglet resulted in significant increases in fuel efficiency, range, balance, and better aircraft control. Reducing induced drag and increasing the lift-to-drag ratio by winglet means millions of dollars of saving in fuel cost for airlines, which has led to its widespread use in modern aircraft [3]. Designers seek access to simplicity, beauty, and efficiency in

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aircraft by observing the main characteristics of animal species that have resulted from thousands of years of their biological evolution. In particular, the main attraction for designers is the combination of structure and function, which is the main characteristic of bird wings [4]. Even in complex urban environments, birds can change quickly from efficient cruise mode to intense maneuvering and precision landing. The malleability of birds allows for a wide variety of wing configurations, each of which can be used for a specific flight mission [5].
Extensive research has been done on winglet design, fabrication, and analysis [18–6, 3, 1]. Numerous experimental and numerical studies have been performed on the application of winglets on aircraft. In the field of experimental studies, Halpert et al. [19] tested different design and installation parameters of the winglet in the wind tunnel on KC-135R aircraft. The results of aerodynamic coefficients showed that the winglet increased the range and flight durability of this aircraft by 6 to 12 percent and reduced fuel consumption up to 8 percent. Sohn and Chang [20] studied the effect of winglets on reducing the strength of wingtip vortices by detecting the flow using the smoke-wire technique. They also studied the effect of winglets on enhancing aerodynamic performance using particle image velocimetry. Gavrilović et al. [14] numerically compared the effect of different shapes of winglets on aircraft and finally increased the lift-to-drag ratio up to 15% in the best case. Narayan and John [6] numerically studied the effect of three different Winglet shapes on the lift-induced drag. They introduced the most efficient winglet in terms of aerodynamic efficiency. Azlin et al. [21] numerically studied the effect of circular and elliptical winglets on the aerodynamic coefficients of the wing or NACA 653218. The results showed that the elliptical winglet increases the lift coefficient up to 8% and achieves the best lift-to-drag ratio.
The effects of winglets and their optimal use are still critical issues in aerodynamics. On the other hand, due to the importance of wing morphing, combining these two issues is a necessity in aerodynamics. Also, improving the performance of the supercritical; wings using the winglets at low Reynolds numbers, especially in landing and takeoff phases, is another issue not addressed in the literature. Therefore, this study focuses on controlling the wingtip vortices with the help of two-dimensional winglets with different installation angles. It must be mentioned that for this purpose, a mechanism has been designed using simple systems with the help of which the winglet can change its mounting angle to the wing. In this research, the effect of different winglet installation angles on the supercritical wing's aerodynamic coefficients has been investigated experimentally in the wind tunnel.

Methodology

This study measured the aerodynamic forces of the wing equipped with a winglet and compared the results with the base wing. This measurement was performed in a good range of angle of attacks from -4 to 20 degrees and at velocities of 8, 15, and 20 meters per second. The selected wing for this study is the supercritical wing with Airfoil NASA Sc(2)-0410, used for high Reynolds numbers and transonic flow regime. It is also used to delay the sudden increase in drag force due to transonic shocks. Since the shape of this wing has minimal curvature, it results in a very low lift coefficient at low and transonic Reynolds. The purpose of this study is to investigate this airfoil at low Reynolds to increase the wing's aerodynamic efficiency at low transonic Reynolds. As a result, these velocities provide a good range for analysis. Winglets are critical in the take-off and landing phases, and aircraft flying in sonic ranges usually benefit from airfoils that do not perform optimally at low Reynolds numbers. Therefore, NASA Sc (2)-0410 wing is fabricated in Dana Laboratory. The geometric characteristics of the wing are reported in Table 1.

Table 1: The geometric characteristics of the wing

Airfoil	NASA SC(2)-0410
chord (cm)	20
span (cm)	53.4

Servo motor and Arduino software have been used to change the angle of the winglet installation. This mechanism can cover angles of 0 to 90 degrees. Hence, this study covered 0^{o} to 90^{o} angles with a 15^{o} step between each. Figure 2 shows the change of the corresponding winglet angle.

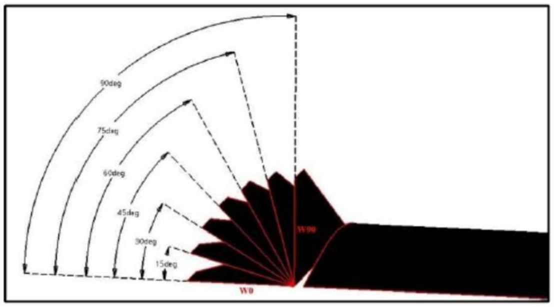

Figure 1: Different installation angles of the winglet relative to the base wing

All experiments have been done in the wind tunnel of the Faculty of Aerospace Engineering of the Amirkabir University of Technology. This wind tunnel has a rectangular test section with 1*1*1.8 square meters and a maximum velocity of 60 meters per second. The general laboratory setup is shown in figure 2. Also, a micro manometer made by Kimo Company has been used to measure velocity with an accuracy of 0.1 meters per second. Forces have been measured with the help of a three-component Balance made by the Planet Company, which can measure drag, lift, and torsional torque. Power sensors have an accuracy of 6 grams or 0.06 Newtons, which is used to measure drag and lift forces.

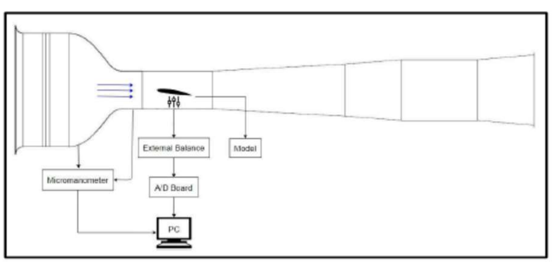

Figure 2: laboratory setup

Finally, by placing the error values of each sensor in the force coefficient equations, a coefficient of 0.000159 is obtained for the measurement error. However, the values of repeated error were higher than the calculated values, which could be due to the accuracy of adjusting the angle of attack and the velocity of the wind tunnel. Because the *repeatability* value is higher, this value is referred to as the test error, equal to 0.001. Therefore, in this research, all the values presented have a positive-negative range of this value.

Results

As mentioned, the lift and drag coefficients play an essential role in an aircraft's initial design and performance analysis. Accordingly, the lift and drag coefficients and lift-to-drag ratio are plotted based on the angle of attack for the base wing and the different angles of the winglet, abbreviated W0, W15 to W90. Figure 3 shows the variation in lift coefficients for velocities at 8, 15, 20 m/s that result in Reynolds numbers of $\mathrm{Re} = 2.73 * 10^5$, $\mathrm{Re} = 2.05 * 10^5$, and $\mathrm{Re} = 1.09 * 10^5$. It is observed that the changes in the lift coefficient are linear, with increasing the angle of attack for all cases. The lift coefficient increases until stall occurs in the wing. The stall angle of this wing is 12 degrees. At this angle of attack, the lift coefficient reaches its maximum value, called the maximum lift coefficient. After stall, any increase in the angle of attack will decrease the lift coefficient. The maximum lift coefficient parameter is essential because its value determines the minimum possible velocity for the level flight of the aircraft so that no stall occurs. Therefore, aircraft designers have always aimed to increase the maximum lift coefficient, especially in the landing and take-off phases. The figure shows that the lift coefficient for all winglets is plotted to thoroughly compare each winglet and the base wing. Therefore, according to the figure, it is clear that adding a winglet to the base wing increases the maximum lift coefficient. In the best case, this value reaches up to 30%. Given this, it can be concluded that the use of winglets for the wings is crucial, especially in the landing and take-off phase when the aircraft needs a maximum lift coefficient. Furthermore, the winglet increases the lift coefficient slope. Winglet reduces the power and size of the wingtip vortex. Therefore, it changes a three-dimensional flow around the limited wing to two-dimensional, increasing the lift coefficient and consequently the lift coefficient slope. Winglets W0 and W15 increased the lift coefficient to the desired value in the angle of attacks higher than 5 degrees and did not perform well in the negative angle of attacks. Increasing the velocity has made the winglet's coefficient slope greater than the wing's coefficient slope. On the other hand, the stall angle is also delayed. However, after comparing the lift coefficient variation for the base wing with different winglets, one can conclude that all obtained results are valid for two velocities of 15 and 20 meters per second.

In other words, the winglet has increased the maximum lift coefficient and the slope of the lift coefficient compared to the base wing. Also, according to the results, with increasing velocity, the effect of the winglet on the lift coefficient decreases.

In the following, the results related to the changes of the base wing coefficient with the winglets with different installation angles at different velocities are shown in figure 4. Winglet's primary role has always been to reduce induced drag by reducing the strength and size of the vortex. This is especially true for the landing and take-off phases of the aircraft because a large percentage of the aircraft's drag in this phase is induced drag. The results show that in many angles, the drag coefficient has decreased. At 8 meters per second, the drag coefficient values were not available at low angles due to the accuracy of the power device. Hence, they were excluded due to errors. Overall, the Winglet W20 reduced the drag coefficient to a desirable value. However, the drag coefficient will decrease with increasing velocity. So W90 is better from this perspective, and increasing the velocity positively affects reducing its drag coefficient. W0 and W15, which were favorable in increasing the lift coefficient, performed well in reducing the drag and kept the drag coefficient constant at almost all velocities. Finally, the best parameter for measuring the aerodynamic performance of an object is its lift-to-drag ratio, which is illustrated in figure 5 for different velocities. Aircraft designers try to design aircraft with the highest lift-to-drag ratio possible at any velocity. The higher the lift-to-drag ratio, the higher the aerodynamic performance of the aircraft. The lift-to-drag ratio increases linearly with increasing angle of attack and then reaches its maximum value at an angle of attack of 4 degrees and then decreases. Of course, the aircraft cannot start flying at this angle because it does not have the required lift, although it has less drag. Therefore, winglets are used for more lift coefficient to choose the optimal point from higher angles. However, the maximum value of this ratio varies for each winglet. Accordingly, winglets are expected to increase this ratio for the base wing by increasing the lift coefficient, decreasing the drag coefficient, and ultimately increasing wing aerodynamic efficiency. As evident in the figures, this has happened at different angles and velocities. In general, Winglet W90 and W45 showed better performance in terms of lift coefficient at the negative angle of attacks. As the angle of attack increases, the winglet decreases the lift coefficient at the angle of attack of 0 to 8 degrees. It should be noted that Winglet W75 has the least reduction in lift coefficient at these angles. In the higher angle of attacks, the Winglet W75 and W15 had the highest increase in the lift coefficient. At second Reynolds number, Winglet W15 performed well in the negative angle of attacks. However, by increasing the angle of attack, Winglet W0 acts as the best winglet. At a velocity of 20 meters per second, the Winglet W15 performed well in the negative angle of attacks, and the Winglet W0 performed very well in the higher angle of attacks. At 8 meters per second, the Winglet W30 has performed better than other choices in terms of aerodynamic performance. The Winglet W0, W15, and W75 perform relatively well and increase the aerodynamic performance of the wing. In contrast, other winglets have reduced this ratio. By increasing the velocity to 15 meters per second, the W0, W90, and W45 had increased the aerodynamic performance of the wing. At a velocity of 20 meters per second, W0 and W15 had the best performance and increased the wing's aerodynamic efficiency.

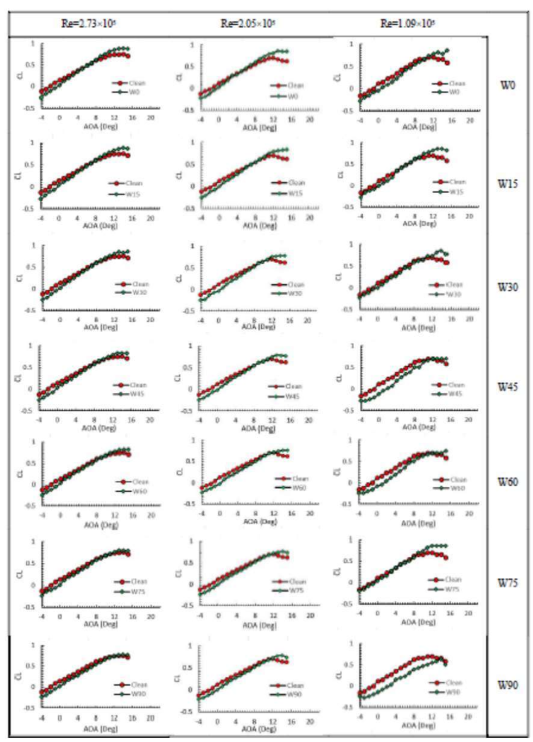

Figure 3: Changes in the lift coefficient with the angle of attack at different velocitys and different angles of the winglet

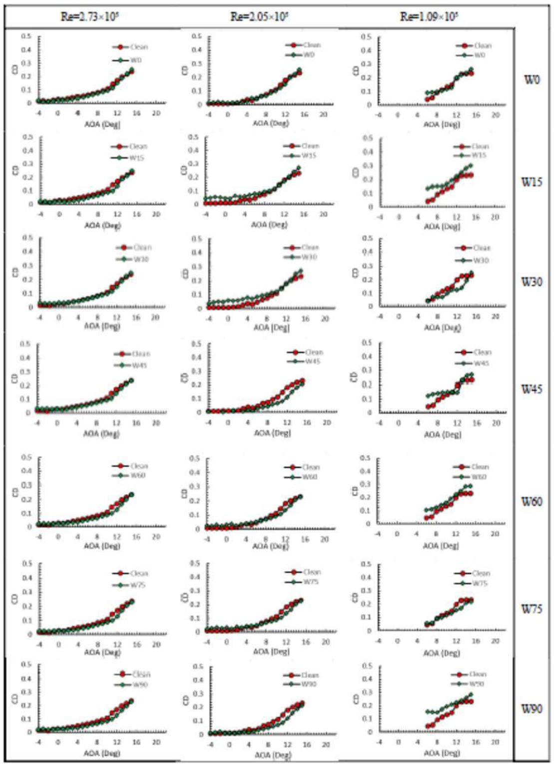

Figure 4: Changes in the drag coefficient with the angle of attack at different velocitys and different angles of the winglet

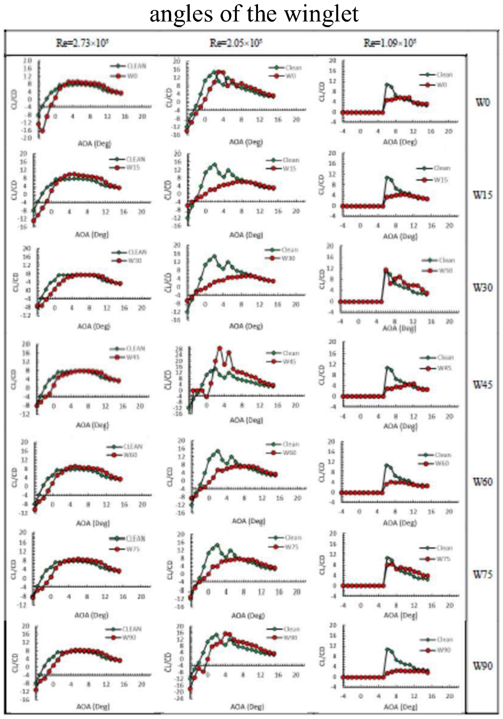

Figure 5: lift-to-drag coefficient changes with the angle of attack at different velocitys and different angles of the winglet

Also, table 2 shows the best winglets in terms of the highest increase in lift coefficient at each velocity and angle of attack to summarize the presented results. As it is known, the best performance is related to Winglet W0 and W15, and these two are introduced as the most optimal angles.

Conclusion

This study focuses on placing the morphing winglet on the aircraft wing. For this purpose, the fabricated mechanism for the wing was designed and constructed to change the angle of the winglet relative to the wing. Also, this research aims to evaluate the performance of different Winglet platforms, change the mounting angle of the winglet relative to the wing, identify the flow field affected by the winglet, and improve the performance of the supercritical wings using the winglet at low Reynolds numbers. Designing a mechanism using simple and efficient systems, experimenting on various platforms and selecting the best platform, and examining the effect of winglets on the supercritical wing at low Reynolds numbers are some of the innovations of this research. This test was performed at velocities of 8, 15, and 20 meters per second and the angle of attacks of -4 to 20 degrees. In this phase, a three-component balance is used to extract the aerodynamic forces of lift and drag coefficient and lift-to-drag ratio parameters. By analyzing the results related to force measurements and determining the lift and drag coefficient and lift-to-drag ratios, for the wings equipped with winglets, the most prominent results are listed below:

In this experimental study, it was observed that Winglets increased the lift coefficients to a desirable level at the angle of attacks after 4°. The drag coefficient also decreased in many samples. In general, by examining the performance of the winglets, it was concluded that the winglet with an angle of 15 degrees (W15) was better at a moderate and negative angle of attacks, and the winglet with an angle of zero degrees (W0) was optimal at a higher angle of attacks. The Winglet W90, which had a 90-degree mounting angle with the wing, had the highest drag coefficient reduction in almost all test conditions, including different velocities and angles of attacks. This study selected supercritical wings with airfoil, and the measurements were made at low velocities. Therefore, it can be stated that winglets can improve the performance of these wings at high angles of attacks during the take-off phase. In general, a winglet with the 0-degree mounting angle is suggested at the take-off phase, when the angle of attack is high and there is a need for more lift coefficient. Then, a winglet with the 90-degree mounting angle (W90) is suggested in the cruise phase, as less lift and drag coefficient is needed.

Table 2: Selection of the best winglet based on the lift coefficient

	-4°	0°	4°	8°	10°	12°	15°
8 m/s	-	-	W15-W75	W15	W15-W75	W75	W75-W0
15 m/s	-	-	-	W0	W0	W0	W0
20 m/s	-	-	-	W0	W0	W0	W0

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