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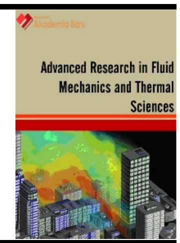

CFD Analysis on the Effect of Winglet Cant Angle on Aerodynamics of ONERA M6 Wing

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Adnan Munshi[1], Erwin Sulaeman[1,*], Norfazzila Omar[1], Mohammad Yeakub Ali[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia
[2] Department of Manufacturing and Material Engineering, Faculty of Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia

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ABSTRACT

Winglets are one of important part of the wing that can reduce the vortex formed at the wing tips and therefore reduce induced drag by partial recovery of the tip vortex energy. Moreover, they increase the effective aspect ratio without actually increasing the wingspan. The geometry of the winglets plays an important role in their task. In the present research, computation of lift and drag of ONERA M6 wing have been conducted using ANSYS Fluent. The results have been validated with the NASA results. Flow features of the entire wing including winglet were examined at different cant angles of winglets of 30°, 60° and 75° at different angles of attack from 3° to 6°. It is observed that among the cases of this study, wings with winglets produces higher C_L/C_D ratio than the normal aircraft wing without winglets up to certain degree of angle of attack and by further increasing to higher angle of attack its performance getting diminished. The investigated concept of adaptable angle winglets appears to be a likely substitute for refining the aerodynamic effectiveness of an aircraft.

1. Introduction

The main purpose of any winglet is to increase the aircraft aerodynamic effectiveness by decreasing the lift induced drag development at the wing tips [1-11, 13-15]. The term winglet was previously used to describe an additional lifting surface on an aircraft. The winglet concept was first introduced by F.W. Lancaster, a British aerodynamicist in the 1800s who proposed the idea that vertical surface at the wing tips could reduce tip vortices but unfortunately it didn't seem to be efficient as the skin friction drag introduced by the new surfaces outweighed the benefits it brought [2]. However, in the late 1970s Whitcomb, a brilliant NASA engineer, developed a groundbreaking research on winglet demonstrating that if the inward flow above the wing and the outward flow below the wing are controlled with properly designed vertical wingtips, it can reduce the vortex energy and reduce the induced drag. Whitcomb and his team provided fundamental design to

* *Corresponding author.*
E-mail address: esulaeman@iium.edu.my (Erwin Sulaeman)

improve the aerodynamic efficiencies of wings and thus reducing fuel and increasing the operating range [4,9].

Winglets can be of various types but their key function is to reduce the aircraft's drag by partial recovery of the tip vortex energy [11]. Wingtip devices can also improve aircraft handling characteristics and enhance safety. A general way of increasing the lift induced drag is to increase the span but that would increase the parasite drag and would require strength enhancements for handling higher weights. The tip vortices are formed due to the pressure imbalances between the upper pressure side and the lower pressure side which is mandatory for a wing to generate lift. However this causes the streamlines to curl which leads to the formation of a vortex, which disrupts the flow field and induce a velocity component in a downward direction called downwash. This downwash causes the relative angle of attack to decrease. The lift vector is tilted backwards and a force component in the direction of the drag appears, called induced drag [12].

Different aspects of winglet are investigated in some literatures. Abdelatief *et al*., [17] performed experimental and numerical analysis on thermal-hydraulic performance of wing-shaped-tubes-bundle heat exchangers equipped with winglet vortex generators. The numerical simulation is performed by using FLUENT. The effects of winglet relative locations, heights, and span angle (θ) on thermal-hydraulic performance enhancement for down-stream and/or up-stream of the bundle on Low Reynolds number are investigated and their effective values are reported.

Feng *et al*., [18] investigated the structural aspect of the winglet structure, where the bending behaviour of the repaired winglet is examined. The ultimate load-bearing capacity and failure mechanism of the repaired winglet structure due to static bending moment load were studied and compared with the undamaged structure.

Amendola *et al*., [19] presented an adaptive winglet, where the winglet is able to perform different configurations during long (cruise) or short (landing/take off) mission phases. A morphing mechanism of the winglet by utilizing movable parts represented by two independent and asynchronous control surfaces with variable camber and differential settings.

Castelani *et al*., [21] and Olson [22] presented flight test reports of a Cessna 525B business jet aircraft equipped with active winglet modification. Castelani [21] performed the Eigensystem Realization Algorithm (ERA), a methodology to construct a time domain curve-fit of decay response data of the flight test. Both the flight flutter test and the flutter analysis have shown that the aircraft equipped with the winglet device is free from flutter within the envelope and up to 1.2 of the dive speed, and therefore complying with the aviation regulation on flutter requirements. Olson [22] performed a verification of the flight test data of the similar aircraft. The results show the efficiency of the model during both wind-up turn maneuver and sideslip maneuver.

Recently Pratilastiarso *et al*., [23] reported their wind tunnel investigation and numerical simulation of wind turbine blade equipped with split winglets. They concluded that the split winglets increase the turbine performance in few cases only. They found that the backflow of the blade tip may cause the reduction of the turbine performance.

ONERA M6 wing has been well known for the study of aerodynamic performance of transonic wing. However, there is no study that considers the effect of winglet on ONERA M6 wing. Therefore, in this study the cruising condition of an ONERA M6 wing will be considered at free stream Mach number of 0.8395 with various angles of attack. The objective is to design and test a winglet configuration capable of increasing the lift-to-drag ratio with respect to the wing without winglets.

To validate the present procedure, a CFD analysis is performed to a scaled down ONERA M6 half wing and validated the results with that of NASA's CFD results [8]. The winglets are added with various cant angles and their effects on the lift-to-drag ratio is studied. The winglets are designed and implemented to the existing ONERA M6 wing in an attempt to increase the aerodynamic efficiency with respect to the standard configuration without winglets.

Most of the commercial long range aircraft has installed winglet to decrease the induce drag to save more fuel, this feature can be also found on the bird. No single shaping of winglets stands out as an optimal geometry, as long as the general guidelines of cant angle, sweep angle, twist angle, taper ratio, airfoil type and length of winglet.

2. Methodology

The computational steps in this project consist of five stages as shown in Figure 1. The project began from preprocessing stage of geometry setup and grid generation. The geometry of the model was drawn using SolidWorks but the flow domain model was modelled using Design Modeler. The dimensions of the plain ONERA M6 wing is shown in Table 1. The grid was generated by mesh in ANSYS. Similar to [25], The second stage was computational simulation by FLUENT solver using Finite Volume Approach. Finally the post- processing stage is conducted where the aerodynamics characteristics of the winglets were examined.

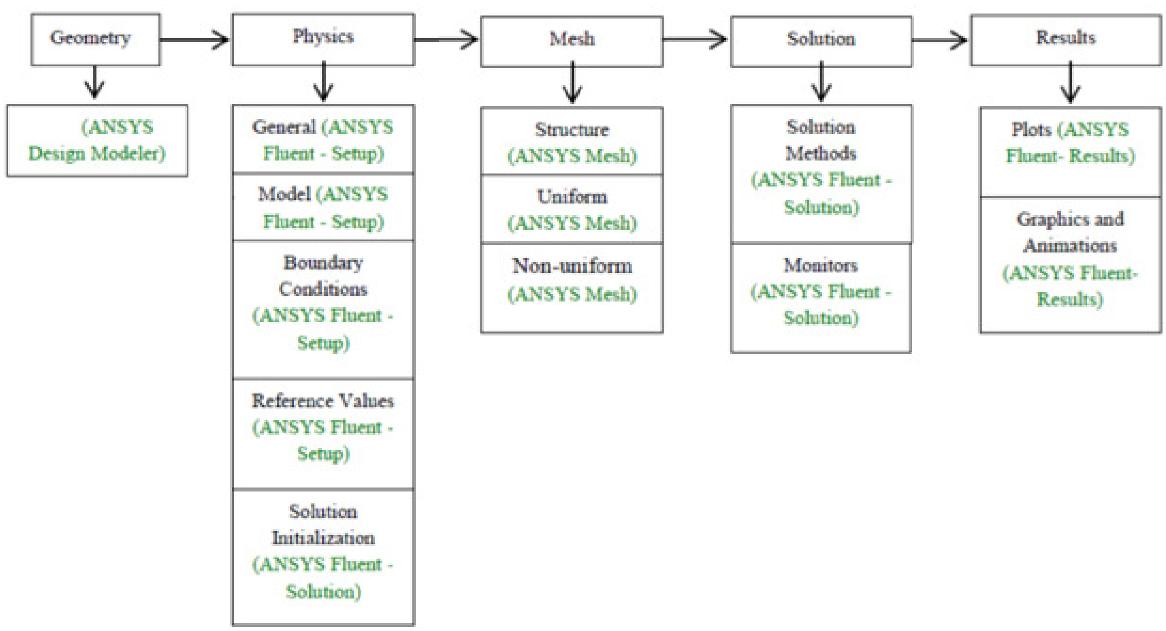

Fig. 1. Flowchart of the stages of CFD

The simulation of this study was done with parallel processing and the method used is finite volume method (FVM). FVM is suitable for using less memory and therefore yielding solutions faster than other methods especially for large problems with high Reynold's numbers. Furthermore, FVM is used for complex shapes like airfoils.

The bullet shape domain was generated by extruding a half hemisphere at the trailing edge of the wing and from the surface of the semi-hemisphere extruding a cuboid. Figure 2 shows the computational domain with the 2 divisions, the small box being the body of influence.

Table 1
Dimensions of ONERA M6 wing

Span (mm)	304.8
Taper Ratio	0.562
Mean aerodynamic chord (m)	164.592
Leading edge (˚s)	30
Trailing edge (˚s)	15.8

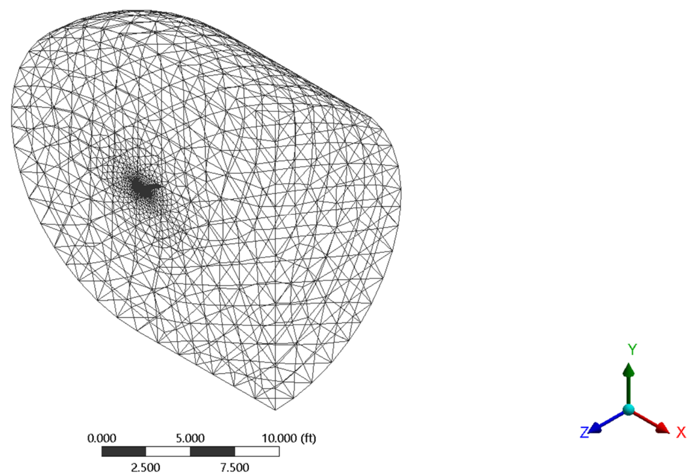

Fig. 2. Meshed flow domain with wing at the centre

As each part of the domain has different element sizes, it is important to note the transition from dense meshing to less dense mesh. For better results, the smoothing has been set to medium in mesh operation. Table 2 shows the element sizes of each section of the domain. The grids were made finer around the trailing and leading edges. Figure 3 shows the mesh of the plain ONERA M6 wing.

Table 2
Element sizes of various sections of the flow domain

Section	Element size (ft)
Flow Domain	0.300
Trailing edge section	0.008
Leading edge section	0.008
Upper Surface	0.002
Midsection	
Lower Surface	0.002
Winglet Upper Surface	0.008
Winglet Lower Surface	0.008

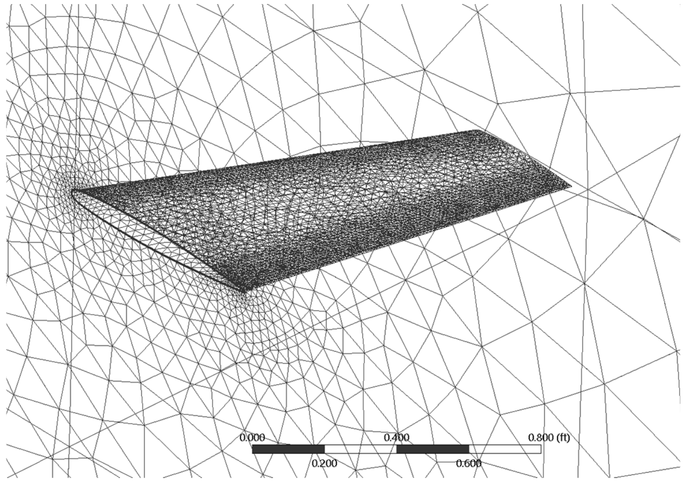

Fig. 3. Mesh of plain ONERA M6 wing

The case is solved using pressure based solver of FLUENT. The options double precision and parallel processing are also selected for more accurate results and faster processing time. For this study, two models are used: the energy model and the viscous model. For the viscous model, the Spalart-Allmaras turbulence model is used as discussed in the literature review for being the most used model for the study of wing tip vortex and winglets. After all the parameters were specified, the model was initialized. The initializing and iteration processes stopped after the completion of the computations. The results obtained were examined and analyzed.

3. Results and Discussions

Mesh sensitivity test was done in order to see if finer mesh yielded much better results. Higher mesh does give better results but it also takes a lot of computational resources. When refining the mesh further does not change the results much, a compromise can be made on accuracy to save further computational resources. Figure 4 shows the different values of Cl and Cd with their respective mesh (The mesh sizes are rounded off to the nearest 10). It can be seen that the difference between Refined Mesh and Refined Mesh 1 is low enough to not refine the mesh any further. Minimum Orthogonal quality and Maximum Aspect ratio of fine mesh are 1.29878e-02 and 1.92499e+02.

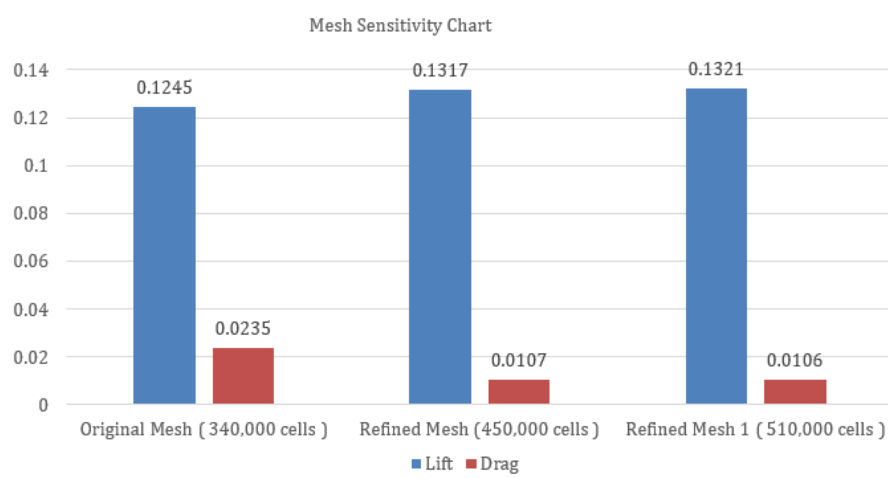

Fig. 4. Bar chart of three mesh sizes and their corresponding lift and drag coefficients

Table 3 shows comparison of lift and drag coefficients. Although the lift coefficient agreed with the NASA CFD results [8], despite continuous attempts in trying to reduce the errors of drag, it was incapable of getting better results. The reason could be due to the maximum number of cells of 510,000 used in the present work. A further refinement of the mesh currently is still in progress.

Table 3
The values of Reynolds number and velocity

	CL	CD	% Difference CL	% Difference CD
NASA CFD	0.1410	0.0088	-	-
Refined Mesh 1	0.1320	0.0106	6.4%	20%

The pressure coefficients were also validated with the NASA CFD results. Figure 5 shows the experimental data as well as the CFD results of the upper and lower surfaces of the aerofoil of the wing at 44% of the span.

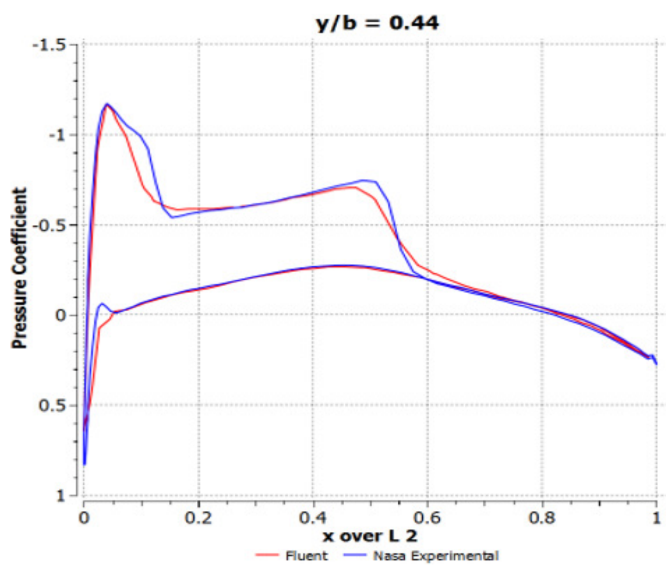

Fig. 5. Pressure coefficients of upper and lower surface of wing

Comparing the graphs of lift coefficients vs angle of attack in Figure 8, it can be seen that the winglet with cant angle of 60° generates the highest lift followed by cant angle 30° winglet and cant angle 75° winglet. No direct relation between the cant angle and lift coefficient can't be concluded from this graph as the trend is not linear.

From the graph of drag coefficient vs angle of attack in Figure 6, it can be observed that the highest drag is also generated by the 60° cant angle wing model whereas the second highest drag is from the wing without the winglet. From this analysis, it is highly likely that the 60° cant angle model could have some modelling deficiencies for it to behave differently than the other two wing models. The two other models comply with the theoretical analysis. The 30° cant angle model is close to the horizon and therefore generates more upward force than the other two models while almost having the least capability to reduce to wing tip vortex. The 75° cant angle model is closest to the vertical and hence should generate less lift than the 30° model but should also have the least drag at low angle of attack due to its reduced wing tip vortex.

Table 4
Cl, Cd ,Cl/Cd and percentage difference of Cl/Cd between ONERA M6 wing with and without winglets

	Angle of attack	3	4	5	6
Without winglet	C_L	0.132	0.1628	0.2188	0.2513
	C_D	0.0106	0.01456	0.0212	0.029
	C_L/C_d	12.45283	11.18132	10.32075	8.665517
60˚ winglet	C_L	0.1496	0.1972	0.2179	0.2103
	C_D	0.01177	0.01586	0.0206	0.0269
	C_L/C_d	12.71028	12.4338	10.57767	7.817844
	% Difference	2.067403	11.20151	2.489306	-9.78214
75˚ winglet	C_L	0.1374	0.1786	0.2233	0.2415
	C_D	0.00944	0.01277	0.0184	0.0291
	C_L/C_d	14.55508	13.9859	12.13587	8.298969
	% Difference	16.88174	25.08278	17.58704	-4.22996
30˚ winglet	C_L	0.1458	0.1923	0.2192	0.2332
	C_D	0.0096	0.0134	0.0184	0.02944
	C_L/C_d	15.1875	14.35075	11.91304	7.921196
	% Difference	21.96023	28.34574	15.42803	-8.58947

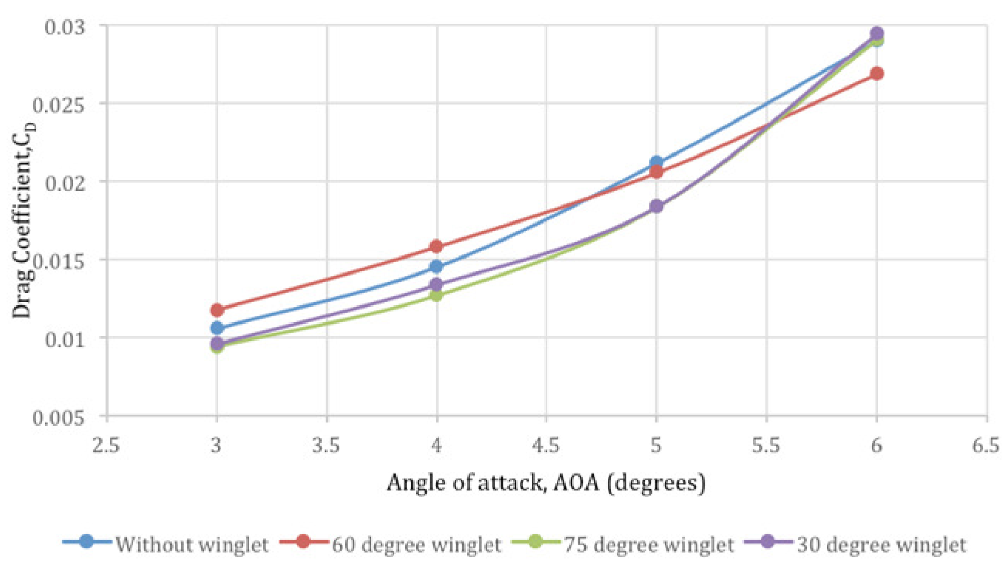

Fig. 6. Drag Coefficient vs Angle of attack of the 4 wing models

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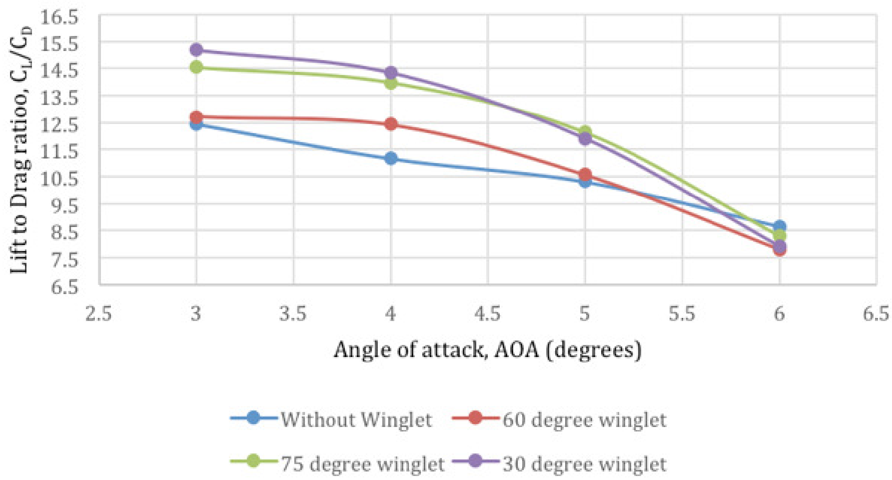

Fig. 7. Lift to Drag Coefficient vs Angle of Attack of the 4 wing models

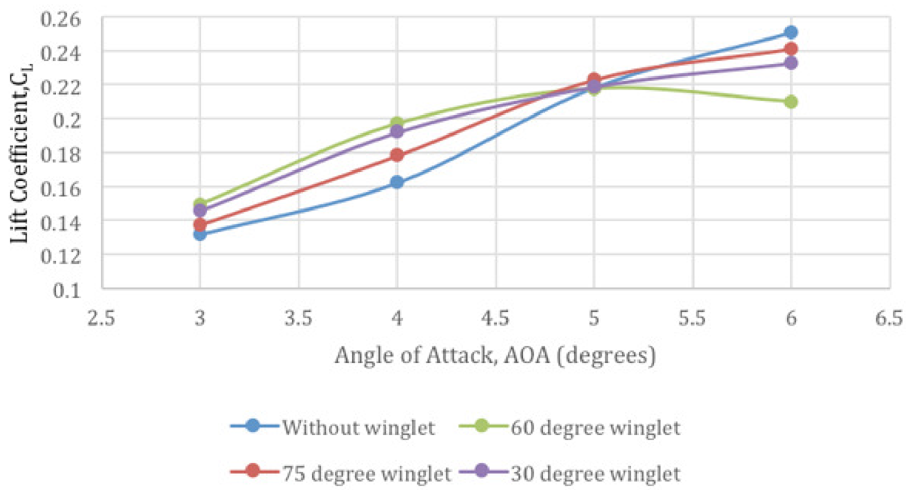

Fig. 8. Lift Coefficient vs Angle of attack of the 4 wing models

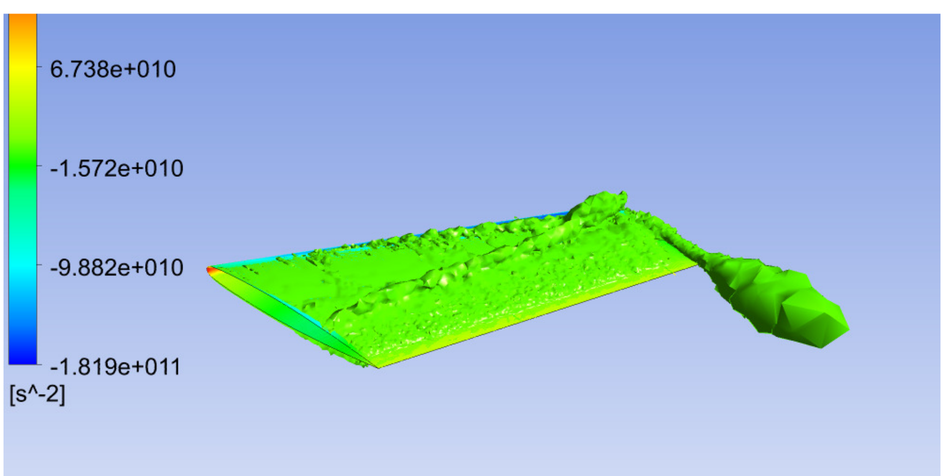

Fig. 9. Vortex core of ONERA M6 plain wing at AOA 3˚

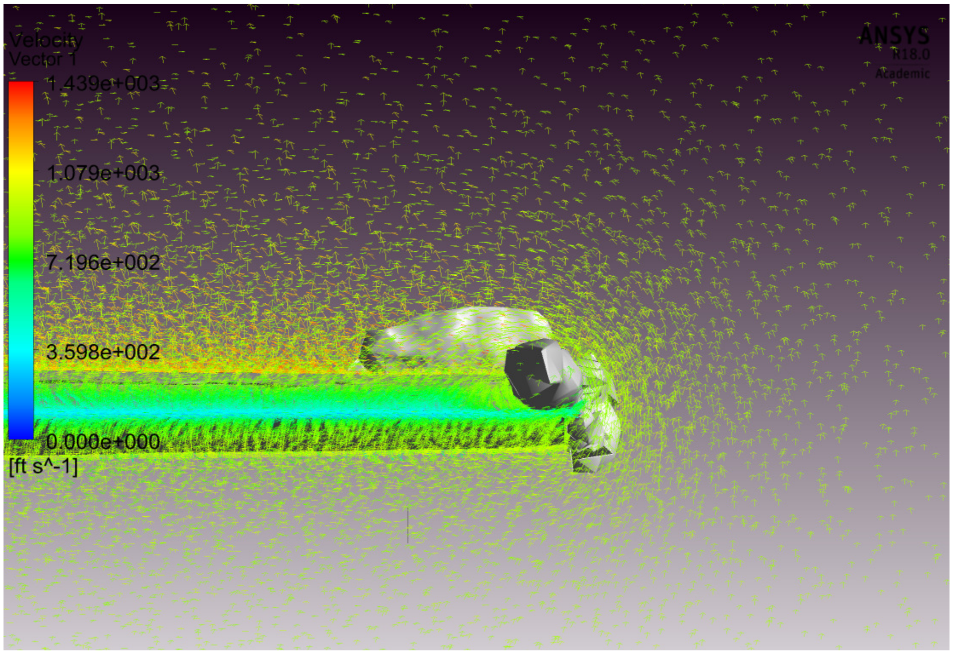

Fig. 10. Velocity vector of wingtip vortex and Q criterion vorticity of ONERA M6 plain wing at AOA 3˚

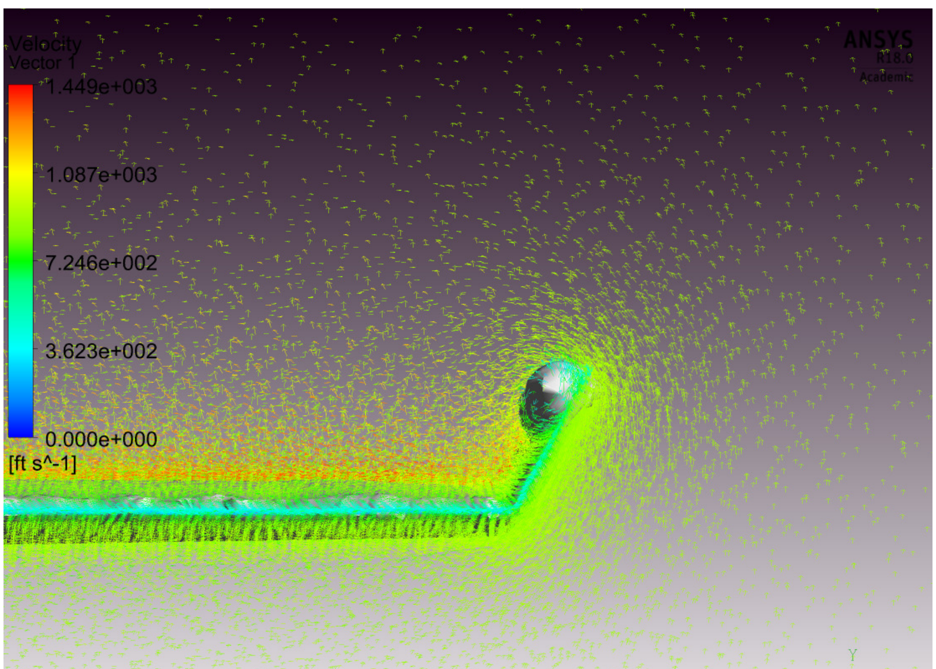

Fig. 11. Velocity vector of wingtip vortex and Q criterion vorticity of ONERA M6 with winglet cant angle 75˚ at AOA 3˚.

Analyzing the graph of lift to drag ratios of all the wing models in Figure 7, it is observed that the wings with winglet has higher lift to drag ratio compared to that without winglets. This deems true to a certain angle after which the performance of the winglet diminishes. From Table 3.1 it can be seen that the percentage difference for Cl/Cd is negative for all winglet model at the angle of attack of 6˚.

Since 75° cant angle winglet is seen on most planes and also the highest increase in performance in this study, the post processing of that model is heighted in the results. Figure 10 and Figure 11 shows the wing tip vorticity at Q criterion of 0.001 for better visualization. It can be seen that the vorticity of the wing without winglet has more vorticity; much of which can be seen sticking to the wing surface whereas the wing with winglet has much lower vorticity mostly concentrated at the winglet tip and therefore not touching the wing surface.

The velocity vectors show a clear visualization of the swirling of flow around the wingtips due to the adverse pressure gradient. These depictions confirm the reduction in vorticity around wings with winglets than those without. Another observation made is that the vortex core for the plain wing is seen to be longer than that of the winglet.

Although the quality of the results conform to the theoretical analysis, the quantitative data in this study appears a bit overstated compared to the researches done previously. Most researches shows a maximum increase in less than 10% for the lift to drag ratios but in this study the values are much higher than 15%. The reason could be due to the maximum number of cells of 512,000 used in the present work. A further refinement of the mesh currently is still in progress.

4. Conclusions

In the field of aeronautics, reducing drag is still a continuous challenge. A typical transport aircraft may have an induced drag as much as 40% of the total drag during cruise conditions. In this work, winglets have been added to an ONERA M6 transonic wing and the performance of the wing after adding winglets has been studied qualitatively and quantitatively. It is found that the present winglet reduces wing tip vortices and induced drag and increases lift to drag ratio up to 25% in transonic cruise regime. Additional winglet area, however, increases parasite drag due to greater wetted surface and may reduce aerodynamic performance at high angle of attack in addition to the increased weight to the device itself. Therefore, it is clear that to achieve all the benefits mentioned above while compromising the short comings, a multi-disciplinary optimization approach should be conducted to exploit the best benefit of the winglets.

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