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PERFORMANCE IMPROVEMENT STUDY OF CESSNA-172 AIRCRAFT USING CFD

Manoviraj Singh S, Arjun Singh, Govindha Rasu N*
School of Mechanical Engineering, VIT University, Vellore, India

ABSTRACT

Three dimensional CFD simulations are carried out for investigating the Cessna-172 aircraft performance with different wing designs. For this the design wing with vortex generator, winglets and extended trailing edge are considered. The angle of attack is varied in the analysis from 0° to 35°. Validation of CFD results is done with the existing wing model. The lift force predicted by the CFD analysis is compared with that of the analytical value. The detailed results of different wing designs are brought out. The pressure and velocity contours along with the lift generated by the each wing designs are discussed. In all the wing design studied with 0° angle of attack, the wing with winglet design produce the maximum lift. Wing with vortex generator design generate more lift at higher angle of attack. Wing design with the combination of both vortex generator and winglets at 0° angle of attack is found to produce lesser lift than the wing with only winglets.

Key words: Cesna-172 Aircraft, CFD, Lift force, Vortex generator, winglets, trailing edge.

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1. INTRODUCTION

Since the wright brother's aircraft first took flight, the world knew that there will be a storm. After the invention of the first aircraft, Travel, Transportation, surveillance, everything became easier and faster. Since then the aviation industry has seen a comprehensive development, from steam engine powered aircraft, which could fly only a few minutes to an hour, to the jet powered engines with planes capable of flying up to a day in a single flight. From then the aerospace industry has developed with leaps and bounds. The main concept which governs the ability of an aircraft to be able to fly is the lift factor; this is majorly generated by the wings.

The Cessna-172aircraft was developed by the Cessna Aircraft Company. It is a company founded in 1927 with its headquarters in Kansas USA. The Cessna-172had its first flight in 1955 [1]. It was originally produced between 1956 and 1986 and was then discontinued. Production then resumed in 1998 and is still produced and used by various civil and defense establishments [2]. The Cessna is a 4 seated aircraft and requires 1 crew member. It has a single engine with high wing fixed wing aircraft. It is the most produced aircraft in the world and is also known to be the most successful aircraft [1].

Table 1 Specification of Cessna Aircraft [3], [4]

Notation	Specification
Length	8.28 m
Wingspan	11.00 m
Height	2.72m
Wing area	16.2 m2
Aspect ratio	7.32
Airfoil	modified NACA 2412
Empty weight	767 kg
Gross weight	1,111 kg
Fuel capacity	212 liters
Propellers	2-bladed metal, fixed pitch
Mean average chord	1.76m

Table 2 Present Performance of the Cessna Aircraft [3], [4]

Notation	Specification
Cruise speed	226 km/h
Stall speed	87 km/h
Never exceed speed	302 km/h
Range	1,289 km
Service ceiling	4,100 m
Rate of climb	3.66 m/s
Wing loading	68.6 kg/m^2

Lift is the force that directly opposes the weight of an airplane and holds it in the air. Most of the lift is generated by the wings [6]. Lift acts through the center of pressure of the object and is directed perpendicular to the flow direction [6-8]. Vortex generators are small components deployed on the wings and stabilizers surfaces. They modify the flow around this surfaces affecting boundary layer [9]. Properly arranged, improve the performance and controllability of the aircraft, particularly at low flight speeds, climb, and high angles of attack [10]. Winglets reduce wingtip vortices, the twin tornados formed by the difference between the pressure on the upper surface of an airplane's wing and that on the lower surface. High pressure on the lower surface creates a natural airflow that makes its way to the wingtip and curls upward around it [11].

Presently the Cessna-172 aircraft is mainly used as a trainer aircraft, for leisure flight, for transportation of goods over small distances and also for air surveillance. In the present study, it was decided to modify the design of the present wing to maximize its lift as the aircraft has a large number of applications in the real world. It is decided to make the aircraft more efficient, as the lift increases, power consumption will be lesser, this in turn implies low fuel consumption resulting in less pollution and more ecofriendly aircraft.

2. MATHEMATICAL MODELLING AND BOUNDARY CONDITION

The conservation equations of mass, momentum and energy are solved using the finite volume method. Fluent software in ANSYS-15 [12] is used for the CFD analysis. In Fluent, There are several turbulence models available. In the present study pressure velocity coupling in done using SIMPLER Algorithm and the second order upwind differential scheme is

chosen for the approximation of the convection terms. A standard k-ε realizable non-equilibrium wall functions are used to predict turbulent flow characteristics in the analysis. All the solution is checked for the normalized residual convergence value of 10^{-5}.
The lift of an aircraft is calculated from Eqn.1.

$$L=C_L * \frac{1}{2} * \rho v^2 s \quad (1)$$

To identify the types of flow over the wings, the Reynolds number is calculated using Eq. 2.

$$Re = \frac{(\delta V x)}{\mu} \quad (2)$$

The thickness of boundary layer is calculated using Eq.3.

$$\boldsymbol{\delta} = \frac{\mathbf{5.0*X}}{\sqrt{\boldsymbol{Re}}} \quad (3)$$

The use of vortex generators helps to control the growth of boundary layer; hence they are most effective inside the boundary layer especially for larger aviation aircraft and airliners. It is typically have a height 80% that of the laminar boundary layer right before the laminar to turbulent transition point on the wing. However for smaller utility aircrafts the size is about $1/8^{th}$ of an inch [13], [14]. In the present study the vortex generator considered to be 3.2mm.

3. GRID GENERATION AND BOUNDARY CONDITION

Modelling of wing is done using Solidworks tool. Then the 3-dimentional model is imported in the Ansys workbench tool. The existing wing model of Cessna-172 aircraft is presented in Fig. 1. As a next step the optimum grid is generated for the wing. Inflation layers are used within boundary layers for better prediction of wall effects Sizing of the mesh was done on the proximity and curvature, with a fine mesh size to obtain accurate results. Grid used for the existing wing of a Cesna-172 is presented in Fig.2. Air is chosen for fluid and the Aluminum is considered for the solid. Inlet velocity is given as 62.7 m/s, this is considered equivalent to the cruise speed of the Cessna-172. All the walls are considered as no-slip walls.

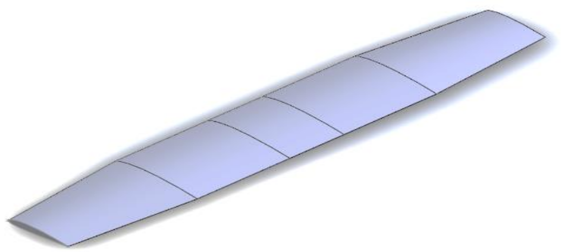


Figure 1 Existing wing model of Cessna172 aircraft with 0° angle of attack

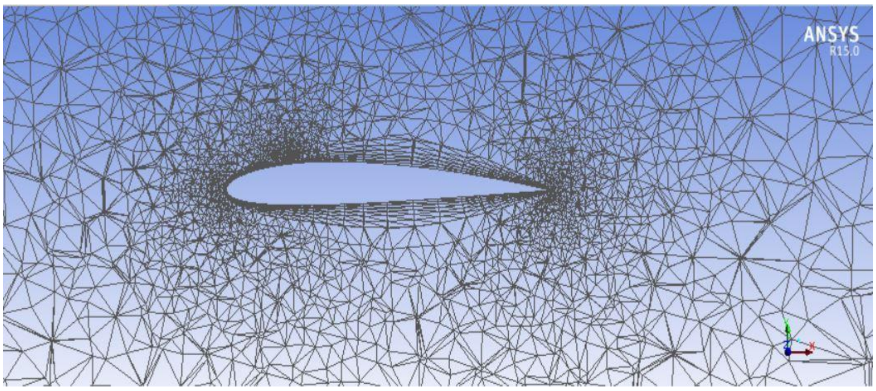


Figure 2 Grid used for the CFD analysis

4. VALIDATION

The wing model presented in Fig. 1 is considered for the validation. For the present wing the lift force is calculated analytically using Eqn. 1 is 7702 N. The coefficient of lift in Eqn.1 is calculated using the XFLR5 tool. The comparison of the lift force between CFD and the analytical value is presented in Fig. 3. The value of lift force is matches within 10% between analytical and the CFD prediction. Hence the CFD procedure is assumed to be validated. The detail analysis of the present wing model and the different design of wing are discussed in the section 5.0.

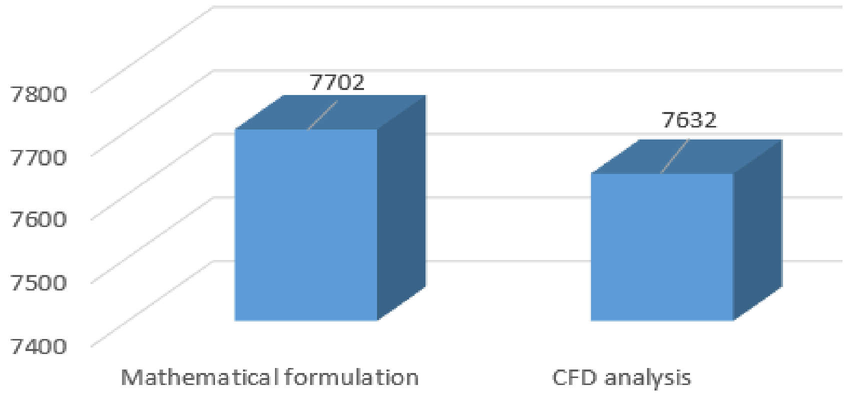


Figure 3 Comparison of Lift (N) between analytical and CFD prediction

5. RESULTS AND DISCUSSION

In addition to the existing wing, four other wing designs are studied as presented in Fig. 4a to Fig. 4d. As a papameter, the angle of attack is studied with various designs of wings. The angle of attack is varried from 0° to 35° and the details of angle of attack for each cases are presented in Table-3. Turbulence at flight was assumed to be 5%. Subsonic flow is considered for the aircraft flight. Flight speed was assumed to be 225 km/h (62.7 m/s) this is a cruise speed for the Cessna [3], [4]. Same speed is considered for all the cases. The influence of cross-stream velocity and other environmental factors are assumed to be negligible. The results of pressure contours, velocity contours and the lift forces are discussed in the successive sections for all the cases.

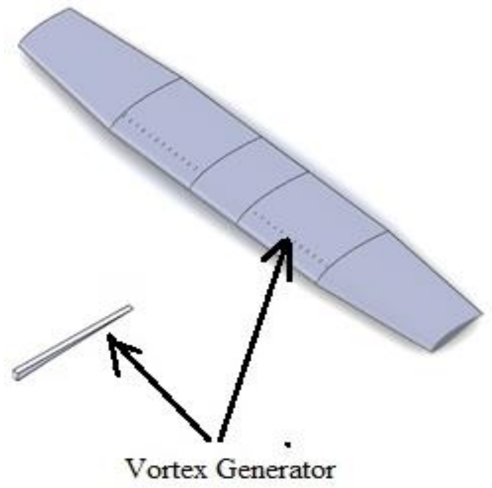


Figure 4a. Geometry of wing with vortex generator

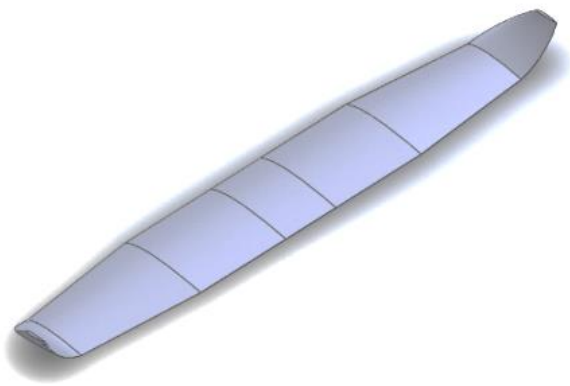


Figure 4b Geometry of wing with winglets

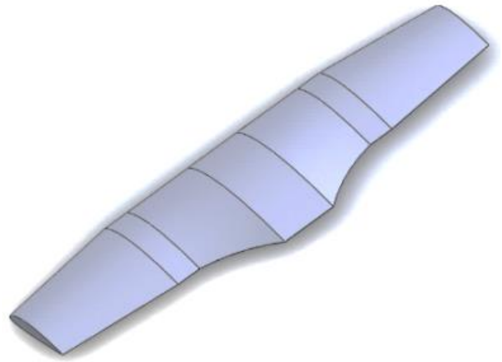


Figure 4c. Geometry of wing with extended trailing edge

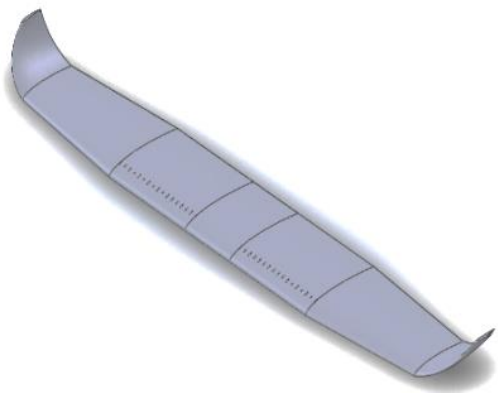


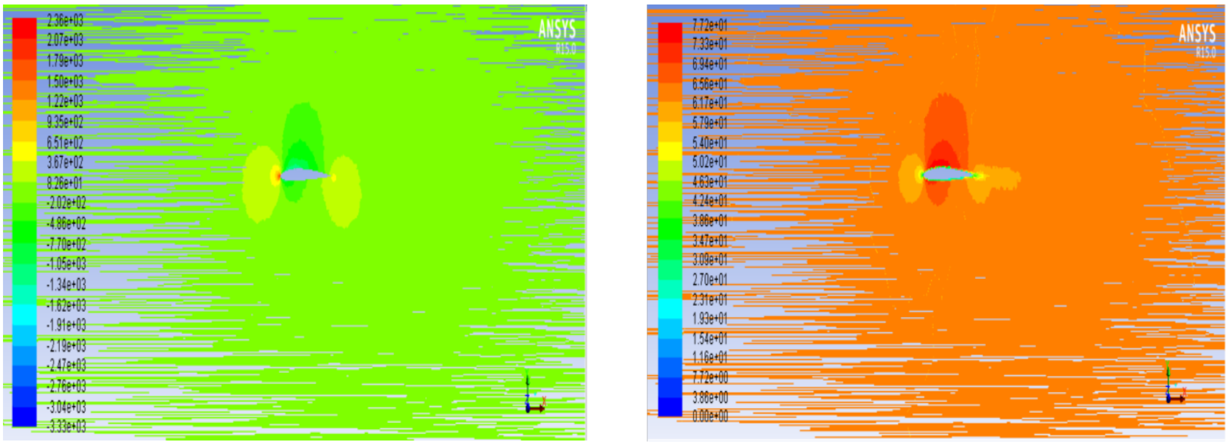
Figure 4d. Wing with vortex generator and winglets

Table 3 Parameters considered for the study

Wing type	Angle of attack (°)
Existing Wing Design	0°
	18°
	22°
	35°
Wing with vortex generator	0°
	18°
	22°
	25°
	30°
	35°
Wing with winglets	0°
	18°
	35°
Wing with extended trailing edge	0°
	18°
	35°
Wing with vortex generaor and winglet	0°
	22°

5.1. Existing Wing Design

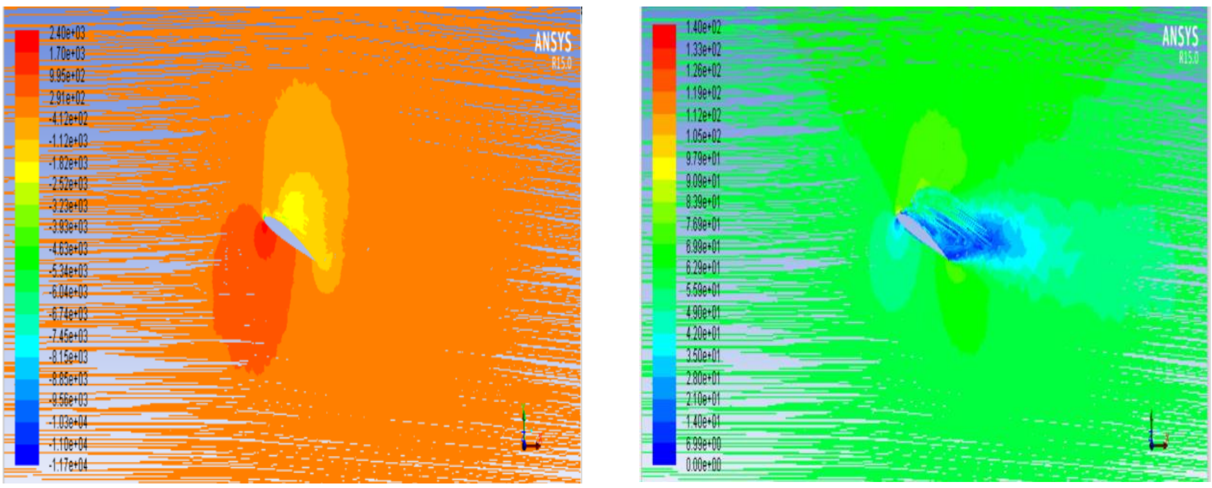
The existing wing is modelled mainly for validation of CFD procedure and also to know the lift force generated. The present wings have no winglets or vortex generators on it as presented in Fig. 1. In this case four different angle of attack is considered, viz, 0°, 18°, 22°, 35°. The pressure and velocity contours on the wing for cruise velocity at 0° angle of attack is presented in Fig. 5a and Fig. 5b respectively. It is clear that high pressure is at the leading edge and trailing edge of the wing. Low pressure s observed at the sides of the wings. Low pressure regions are longer on the top of the wing compared to bottom. This is due to the higher velocity at the top of the wing; this can be seen at Fig. 5b.



[a] [b]

Figure 5 [a] static pressure distribution on the wing **[b]** velocity contours on the wing at cruise velocity at 0° angle of attack

The pressure and velocity contours on the wing for cruise velocity at 22° angle of attack is presented in Fig. 6a and Fig. 6b respectively. The flow pattern is different from the previous case. Relatively high pressure zone is observed in the bottom compared to top of the wings. Negative pressure is observed at top. This is because the vortex generator delays the boundary layer separation and improves stall characteristics. The peak velocity is observed to be double that of previous case. Also low velocity is observed for longer distance from the downstream of the wing. As discussed in previous section the lift force for the present wing is found to be 7632 N.



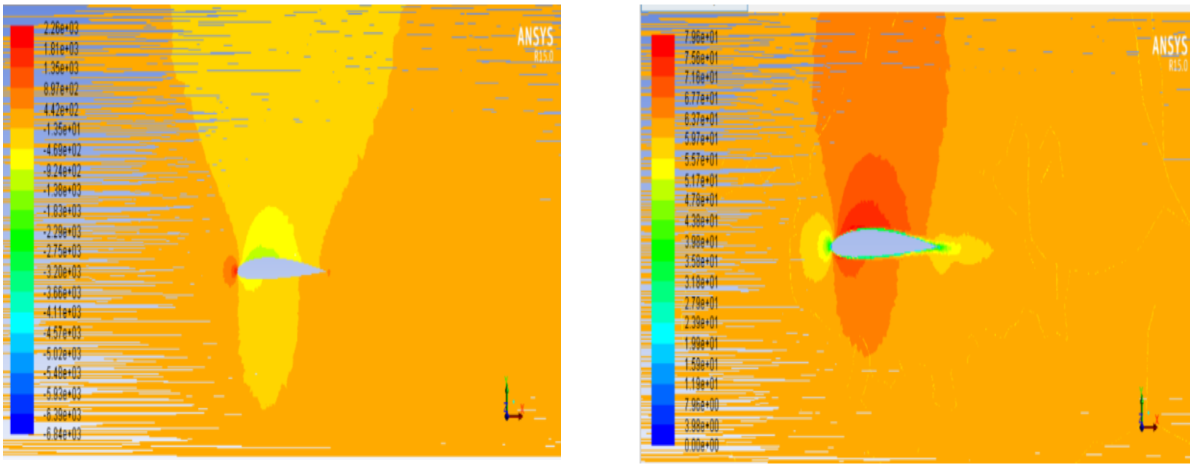
[a] [b]

Figure 6. [a] static pressure distribution on the wing **[b]** velocity contours on the wing at cruise velocity at 22° angle of

attack

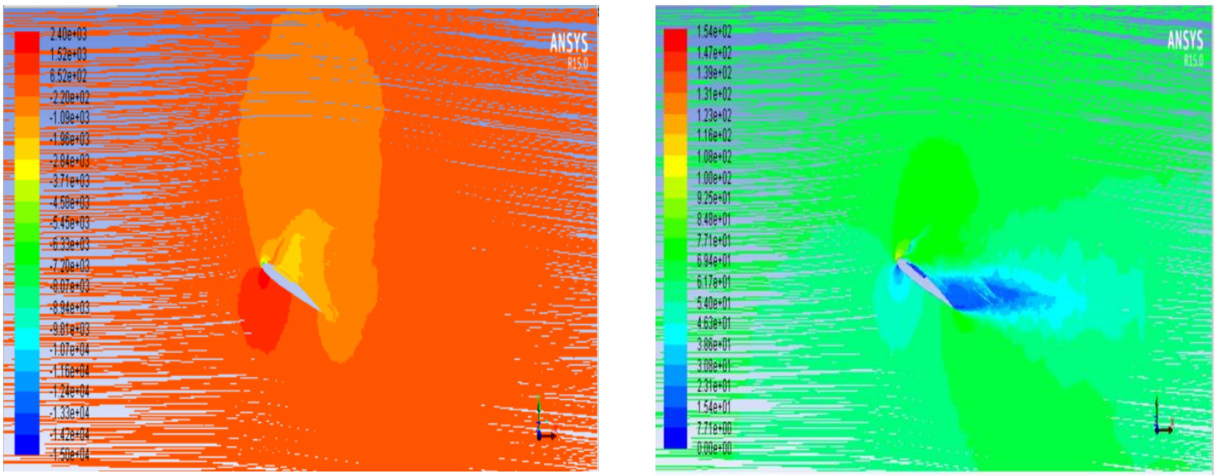
5.2. Effect of Wing with Vortex Generator

It is decided to change the existing wing design for better lift force. Towards this vortex generators are modelled on the wings, as presented in Fig. 4a. Vortex generators are placed equally along the leading edge. Totally 13 numbers of vortex generators are considered on each sides of the wing. For this case four different angle of attack is considered, viz, 0°, 18°, 22°, 25°. The pressure and velocity contours on the wing with vortex generator for cruise velocity at 0° angle of attack is presented in Fig. 7a and Fig. 7b respectively. In this case the distribution of pressure is very different than the existing wing. Because the presence of vortex generator is obstruct the flow and increase the velocity. It is easily understood that the effect is far felt on the top of the wing, as the low pressure zones are observed. The lift force generated in this case is 7333 N. It is to be noted that this lift value is lower than the value in the existing wing. This is due the higher pressure on the top of the wing compared to the existing case. Also, the pressure and velocity contours on the wing with vortex generator for cruise velocity at 22° angle of attack is presented in Fig. 8a and Fig. 8b respectively. The similar trends are observed as the previous case except that the effect of vortex generator is felt far from the wing. It means that the region of low pressure extended in this case.



[a] [b]

Figure 7 [a] static pressure distribution on the wing with vortex generator [b] velocity contours on the wing with vortex generator at cruise velocity at 0° angle of attack

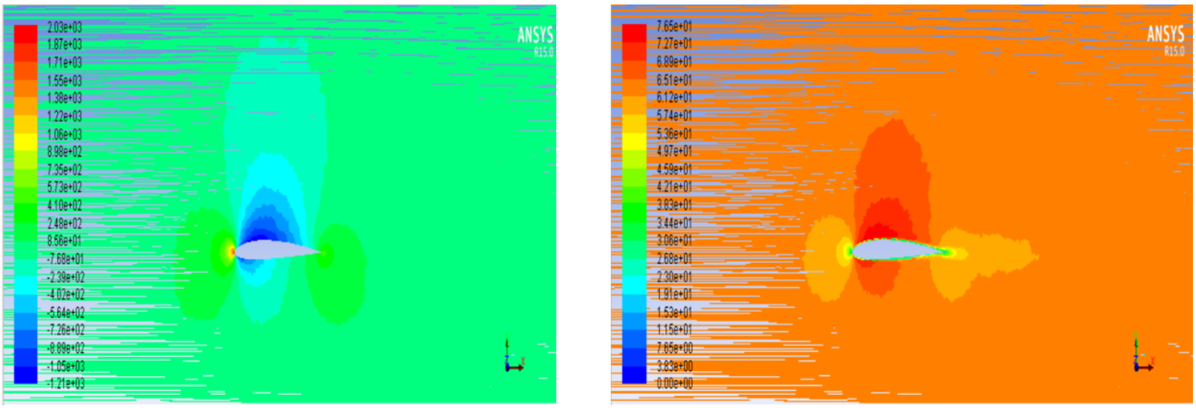


[a] [b]

Figure 8 [a] static pressure distribution on the wing with vortex generator [b] velocity contours on the wing with vortex generator at cruise velocity at 22° angle of attack

5.3. Effect of Wing with Winglets

As the design of wing with vortex generator is not enhancing the lift force, it is decided to change the wing configuration further for improvements of lift force. Towards this winglets are modelled on both sides of the wings, as presented in Fig. 4b. In this case three different angle of attack is considered, viz, 0°, 18°, 35°. The pressure and velocity contours on the wing with winglets for cruise velocity at 0° angle of attack is presented in Fig. 9a and Fig. 9b respectively. Compared to previous cases in this low pressure zone on the top of the wing is very large. It is clearly visible that after adding the winglets the pressure distribution is such that the lift increases, this is because after adding winglet the vortex drag forces reduces on the wingtip and hence lift increases. The lift force generated in this case is 9152 N.

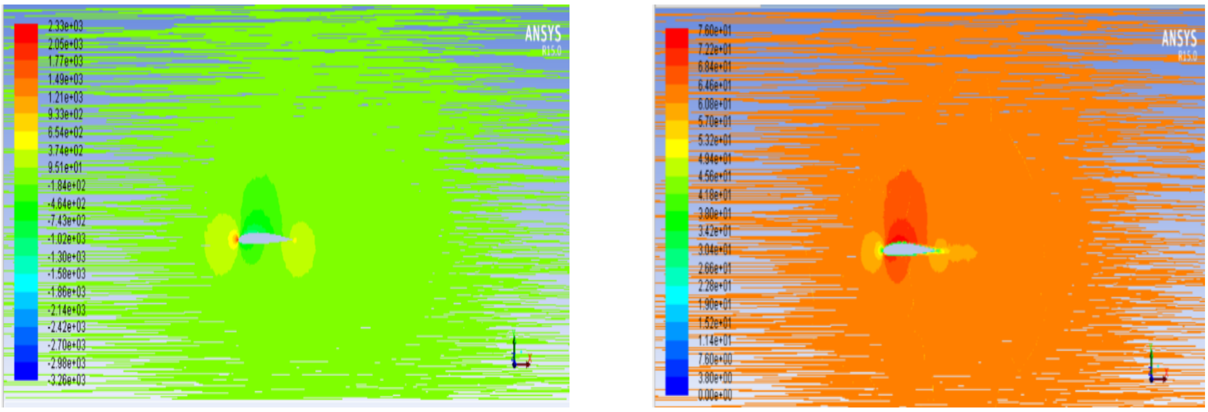


[a] [b]

Figure 9 [a] static pressure distribution on the wing with winglets [b] velocity contours on the wing with winglets at cruise velocity at 0° angle of attack

5.4. Effect of Wing with Extended Trailing Edge

In addition to the winglets it is decided to study further any other modifications on the wing will increase the lift. Towards this trailing edge on the wing has been extended. Towards this extended trailing edge is modelled on the wings, as presented in Fig. 4c. In this case three different angle of attack is considered, viz, 0°, 18°, 35°. The pressure and velocity contours on the wing with extended trailing edge for cruise velocity at 0° angle of attack is presented in Fig. 10a and Fig. 10b respectively. By extending the trailing edge there is an increase in the area and this contributes for the lift. The lift generated in this case is 7674 N. This value is little more than the lift generated in the existing wing. It is to be noted that the low pressure on the top of the wing is almost in the same range as in the case of existing wing and less than that of wing with winglets.

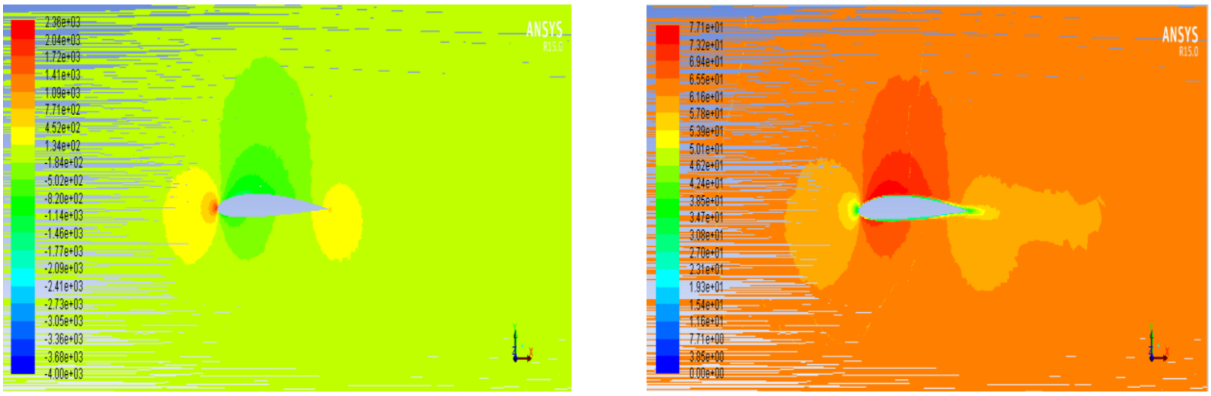


[a] [b]

Figure 10. [a] static pressure distribution on the wing with extended trailing edge [b] velocity contours on the wing with extended trailing edge at cruise velocity at 0° angle of attack

5.5. Effect of Wing with Vortex Generator and Winglet

After the analysis of effect of individual parameters on lift, it is decided to study effect of combination of parameters. Towards this the combination of individual parameters have is chosen i.e. wing with vortex generator and winglets. The geometry used for this analysis is presented in Fig. 4d. In this case two different angle of attack is considered, viz, 0° and 22°. The pressure and velocity contours on the wing with vortex generator and winglets for cruise velocity at 0° angle of attack is presented in Fig. 10a and Fig. 10b respectively. The lift generated in this case is 8716 N. This value is more than the lift generated in the existing wing but less than the wing with winglets alone. Hence, it is well understood that, using of vortex generator tend to reduce the lift and the winglets enhances the lift. The pressure and velocity contours on the wing with vortex generator and winglets for cruise velocity at 22° angle of attack is presented in Fig. 11a and Fig. 11b respectively. In this case the pressure and the velocity patterns are very different from the other cases.



[a] [b]

Figure 11. [a] static pressure (Pa) distribution on the wing with vortex generator and winglet [b] velocity (m/s) contours on the wing with vortex generator and winglet at cruise velocity at 0° angle of attack

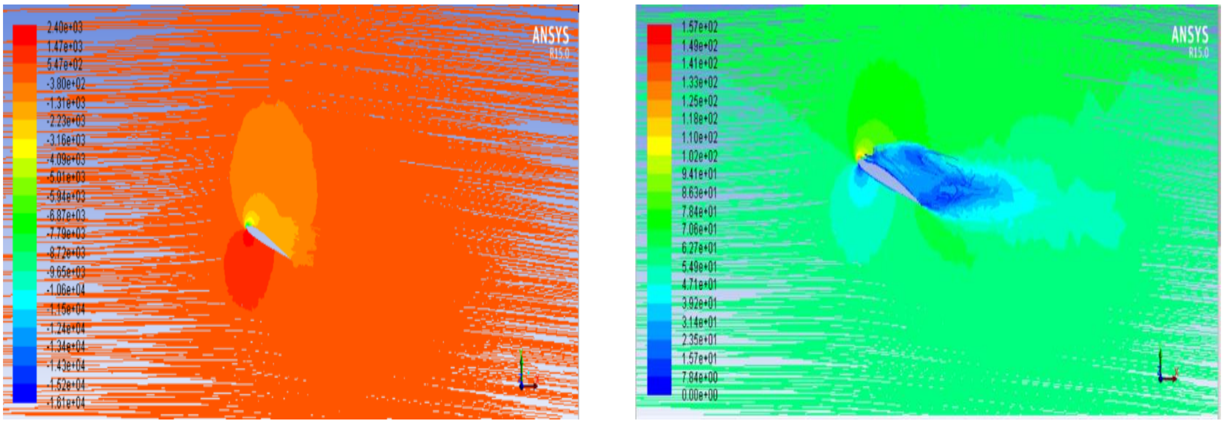


Figure 12. [a] Represents the pressure value above and below the wing, [b] Shows the fluid flow at customary condition for wing with vortex generator and winglet at 22°

5.6. Comparison of Lift force Generated

Lift generated in each case is different. Comparison of lift force (N) generated with different parametric study is presented in Fig.13. For this comparison 0° angle of attack is considered. It is understood that lift value decreases on incorporating the vortex generator on the wings. This is due to fact that vortex generators are disrupt the flow on top of the wing because of that the pressure increases, as a result the lift reduces. However after analysis of the wing at varying angle of attacks we found that boundary layer starts to form between the wing angles 21-22°. The wing with vortex generator at 22° angle of attack is contributes for higher lift.

The Lift value is found be 53168 N were as the lift for the existing wing at the same wing angle is 45,865 N.

From this figure, it is clear that wing incorporated with winglets provides maximum lift. This is due to fact that winglet reduces the drag caused at the wingtips. The analysis of wing with a combination of both winglet and vortex generator yields a lift value of 8716 N at 0° and 63528 N at 22°.

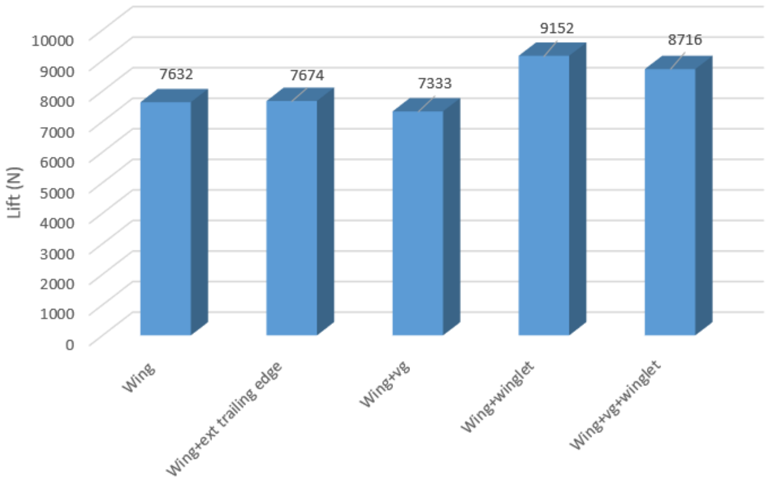


Figure 13 Comparison of Lift force (N) at 0° angle of attack

6. CONCLUSIONS

Three dimensional CFD simulations are carriedout for investigating the Cessna-172 aircraft performance under different geometric conditions. For this the design of vortex generator, winglets and extended trailing edge are considered. The angle of attack is varied from 0° to 35°. The results of pressure and velocity contours along with the lift generated by each case are brought out. Validation of CFD results is done for the existing wing model. The lift predicted by the CFD analysis is compared with that of the analytical value. The major conclusions of this study are

- Wing at 0° angle of attack, in all the cases studied the wing with winglet design produce the maximum lift value
- Wing with vortex generator design generate more lift at higher angle of attack.
- Wing design with the combination of both vortex generator and winglets at 0° angle of attack is found to produce lesser lift than the wing with only winglets, but at higher angle of attack it produce the more lift.

NOMENCLATURE

C_L-Coefficient of lift

ρ - Density of air (kg/m^3)

v - Cruising speed (m/s)

s - Planform area (m^2)

V - stall speed (m/s)

x - Chord length (m)

µ - Dynamic viscosity (kg/m-s)

δ - Boundary layer height (m)

X - Transition point (16% of the chord) (m)

Re - Reynolds number

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