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Enhancing aerodynamic performance of NACA 4412 aircraft wing using leading edge modification

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Abstract. This work deals with designing the aircraft wing and simulating the flow behavior on it to determine the aerodynamically efficient wing design. A NACA 4412 airfoil is used to design the base wing model. A wing with a rectangular planform and the one with curved leading edge planform was designed such that their surface areas are the same. Then, a comprehensive flow analysis is carried out at various velocities and angle of attacks using computational fluid dynamics (CFD) and the results were interpreted and compared with the experimental values. This study shows that there is a significant improvement in the aerodynamic performance of the curved leading edge wing over the wing with rectangular planform.

Keywords: coefficient of lift; coefficient of drag; L/D ratio; NACA; CFD; ansys fluent

1. Introduction

The interaction between the moving object and the air is termed as aerodynamics. It deals with the forces and motion of aircraft through the air(Anderson 2013). All aircraft manufacturers are looking forward to improving the efficiency of an air-wing by increasing the lift to drag ratio. The efficiency of the aircraft depends on various parameters, like lift, drag, and lift to drag ratio (Kundu *et al.* 2016). These parameters in-turn depend on the design of the aircraft wing (Mannion *et al.* 2018). For any object moving in the air, four forces act on it. The one which helps in propelling the object is called thrust, the objects own weight acts downwards and the force hindering the forward motion is called drag which acts opposite to the direction of the motion; the force acting upwards and perpendicular to the direction of motion is called lift (Haque *et al.* 2015). The weight of the aircraft cannot be altered below a specified value and thrust is the propelling force produced by an engine, whose capacity is also fixed. So we are left with the remaining forces lift and drag which can be changed in order to increase the aerodynamic efficiency, i.e., the ratio of lift and drag of an aircraft. In general drag is of many types, viz., pressure drag, profile drag, induced drag, skin friction drag, etc. Our main objective is to decrease the pressure drag which can be achieved by streamlining the body as much as possible as a result of which the flow leaves the trailing edge of the wing smoothly and produces lesser area of wake. These techniques have shown a significant reduction in total drag (Mouhsine *et al.* 2018, Haoqin *et al.* 2015). Lesser drag leads to less fuel consumption and hence reduces the operating cost of the aircraft. A suitable design modification in aircraft parts can alter the complete aerodynamic performance. There are various wing design studies reported in the literature to improve the aerodynamic efficiency of the aircraft (Lu *et al.* 2011, Dong and Lu 2007, Saranprabhu *et al*. 2017, Booma Devi and Shah 2017, Kumar 2018). An experiment was conducted by (Dwivedi *et al*. 2013) on aerodynamic static stability analysis on different types of wing shapes. The reduced scale size wings of various shapes like a standard rectangular wing, rectangular wing with a curved tip, tapered wing and tapered wing with a curved tip, etc. were tested in a low-speed subsonic wind tunnel for various airspeeds and angles of attack. They concluded that the tapered wing with curved tip was the most stable at different velocities and ranges of the taken angles of attack.

(Keerthana and Harikrishna 2017) carried out wind tunnel investigation on the aerodynamics of 2:1 square section for various angle of incidence and shown that area of wake dominates on the total drag of the object. They proposed various methods of reducing the pressure drag. (Ghasemi *et al.* 2014) studied the aero-elastic characteristics of a wind turbine composite blade. They used both analytical and numerical scheme to study the aero-elastic behavior of wind turbine blade and shown that design modification of airfoil section plays an important role in the overall performance of the wind turbine.

(Kaynak and Flores 1989) studied transonic flow around the low aspect ratio airfoil in the wind tunnel. They applied the Euler/ Navier-Stokes zonal approach to study the flow pattern and showed that geometric changes strongly dominate on the aerodynamic forces on the airfoil. (John *et al.* 2016) carried out aerodynamics study on NACA 2412 airfoil using computational fluid dynamics approach and have shown that geometric changes significantly improves the aerodynamic efficiency.

(Pinkerton and Robert 1938) studied the variation of pressure distribution over a NACA 4412 airfoil for different Reynolds numbers. The experiment was conducted for a

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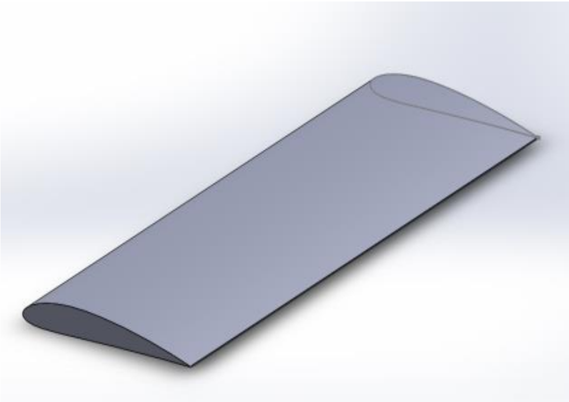
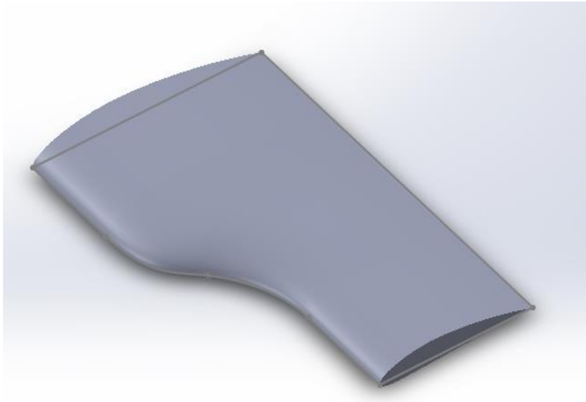


(a) Rectangular wing



(b) Curved Wing

Fig. 1 Wing model for rectangular and curved leading Edge Planforms

rectangular model of NACA 4412 in the variable density tunnel for the angle of attacks from -20 degrees to 30 degrees and for Reynold's Number from 1,00,000 to 82,00,000 approximately. Their results showed that slight geometric modification gives an appreciable improvement in the lift and L/D. (Haque *et al.* 2015) carried out an experimental investigation to explore aerodynamic performance by incorporating curvature at the leading edge of a wing. A wooden model with straight leading and trailing edge i.e. rectangular planform and another model with a curved leading edge and straight trailing edge were fabricated with NACA 4412 aerofoil in equal length (span) and surface area. Both the models were tested in a closed-circuit wind tunnel at an airspeed of 0.07 Mach. Results showed that wing with curved leading edge had better aerodynamic performance than a rectangular wing.

(Okonkwo and Smith 2016) presented a comprehensive review of evolving trends in blended wing body aircraft design and showed that geometric changes on aircraft wing enhance the aerodynamic efficiency of the aircraft.

(Booma Devi and Shah 2017) have carried out a comprehensive analysis over an airfoil with different kinds of dimples to look at the effects of such projection on the total lift and aerodynamic efficiency of the wing. (Saranprabhu *et al.* 2017, Borna *et al*. 2013) carried out flow analysis using computational fluid dynamics tool Ansys Fluent and studied the effects of airflow interaction over the surface of a supersonic aircraft and plates.
(Abbishek *et al.* 2017, Kumar 2018, Ozmen 2013, Kumar *et al.* 2017) carried out a comprehensive flow and structural analysis of aircraft fuselage and wind turbine blades using Ansys Fluent. (Mouhsine *et al.* 2018) carried out aerodynamics and structural analysis of wind turbine using Ansys Fluent and studied the reliability of wind turbine blades through the development of the airfoil structures. (Piedra *et al.* 2018) carried out the computational analysis of a light-sport aircraft and showed that wing twist and taper strongly dominate on the aircraft performance.

(Qin *et al*. 2018) studied large eddy simulation of unsteady flow over a stationary airfoil and have made several changes in the airfoil geometry and flow parameters. They concluded that optimum geometry change leads to enhancement in the performance of the airfoil. (Chamorro *et al.* 2013, De Gregorio 2012) carried out a comprehensive flow analysis on the airfoil for wind turbine and for helicopter using Fluent. They have shown that geometric changes such as adding vortex generators or making modifications at the leading/ trailing edge of the airfoil profile lead to a significant improvement in the overall airfoil efficiency. There are various studies reported on the computational analysis of the aerodynamics and design modifications in airfoils and wind turbine blades (Zhao *et al*. 2014, Aresti *et al*. 2013, Lin *et al.* 2016, Unchai and Janyalertadun 2014, Ozmen 2013).

In the present work, we analyzed the effect of the curved leading edge on the aerodynamic performance of an aircraft wing. Rectangular planform wing is taken as a reference and results are compared with the experimental results of (Haque *et al.* 2015). Computational fluid dynamics results have shown close agreement with the experimental results as of Haque *et al.* (2015).

2. Design and simulation

2.1 Wing models

The geometry for the rectangular wing of NACA 4412 (according to the nomenclature, it has a maximum camber of 4% located at 40% of the chord from the leading edge with a maximum thickness of 12% of the chord) was created using Solidworks software. The standard coordinates of the airfoil were taken and scaled down to a chord length of 127 mm and a span of 245 mm.

The same model was edited to get the curved leading edge planform. The curve on the span of the wing is made with the given dimensions, which vary with each quarter of the span(S). The profile of the curve is given as :
The chord length at each quarter of the wingspan is as follows:

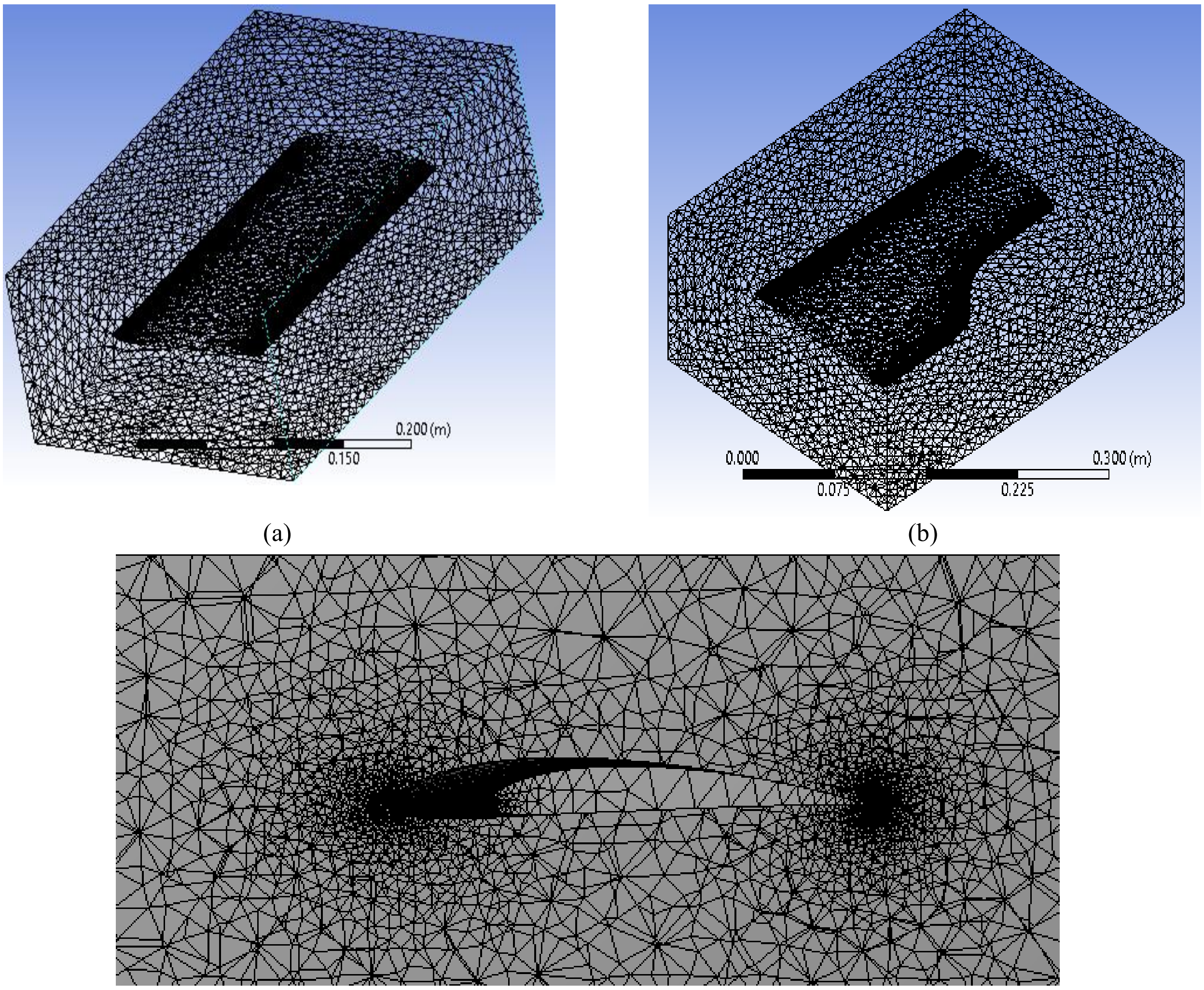


Fig. 2 (a) Meshed rectangular wing, (b) Meshed wing with a curved leading edge and (c) Cut sectional view of the wing

(i) From x=0 to 0.25S, C=152.4 mm
(ii) From x=0.25S to 0.5S, C=140 mm
(iii) From x=0.5S to 0.75S, C=110 mm
(iv) From x=0.75S to S, C=101.6 mm

2.2 Simulation procedure

The geometries created were then imported to the CFD software, Meshing is then carried for the flow domain and a smooth transitional inflation layer with transition ratio of 0.272 was provided. The mesh generated had nearly 1552891 elements and around 271211 nodes.

The dimensionless wall distance y+ was approximately equaled to 1 as we adopted a near-wall model approach (mesh refinement). Figs. 2(a) and 2(b) show the meshed models for rectangular planform wing and a curved leading edge wing respectively. Fig. 2(c) is the meshed cut section of the wing and shows the side view from the tip of the wing.

2.3 Boundary conditions

ANSYS Fluent was used to study the complex flow patterns over the wings for the simulation and the standard k-ε turbulence model is used. We selected the k-epsilon model because our main objective was to compare aerodynamic efficiencies viz, maximum coefficient of lift which occurs at the point of stall. For the fully attached flow k-epsilon model gives best results but if one wants to study the effect of wake regions and vortex shedding i.e., flow situations at high angles of attack in that case k-epsilon is not suitable then one has to go for k-omega model.

The boundary conditions were taken at inlet velocity with the direction and magnitude. The solution method that was used to solve were SIMPLE Scheme of Pressure-Velocity Coupling and second-order numerical schemes.

2.4 Mesh independency test

Mesh sensitivity analysis was carried out as in Table 1 and it was found that results don't show much variation beyond the 1552891 elements and 271211 nodes

Table 1 Mesh sensitivity study

Elements Number	Coefficient of lift (C_L)	Coefficient of drag (C_D)
442467	0.9776	0.4638
979804	1.4327	0.3236
1156924	1.3575	0.3463
1467380	1.2416	0.3787
1552891	1.13375	0.37566
1676830	1.13353	0.37575

3. Results and discussion

The aerodynamic forces for both the wings at a speed of 25m/s, 35 m/s and, 45 m/s for various angles of attack have been calculated. We observed a significant improvement in the lift coefficient for the curved leading edge wing compared to the rectangular aircraft wing. Results are then compared with the experimental values as of (Haque *et al*. 2015). We can observe that for a particular velocity, the aerodynamic efficiency of the wing with a curved leading edge is higher than that of the rectangular wing as C_L increases and L/D also increases.

Fig. 3 shows the variation of coefficient of lift with angles of attack at 25 m/s velocity and it is clearly visible that the wing with curved leading edge modification has maximum lift coefficient with an angle of the stall in between 11- 12°. From Fig. 4, it can be seen that at the same speed and geometric dimensions wing with curved leading edge modification shows improved aerodynamic efficiency over its rectangular counterpart. The average increment in aerodynamic efficiency with curved wing compared to rectangular wing is found to be 10%.

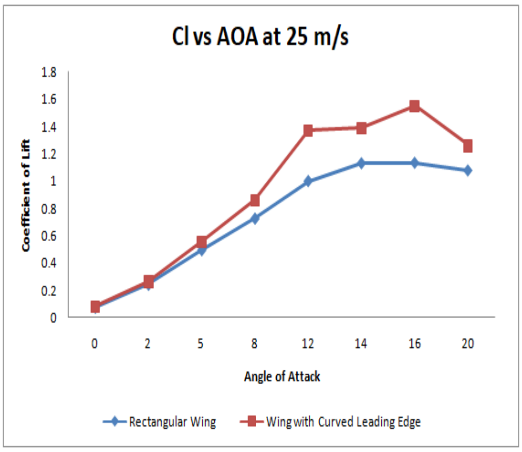


Fig. 3 Variation of the coefficient of lift with angles of attack

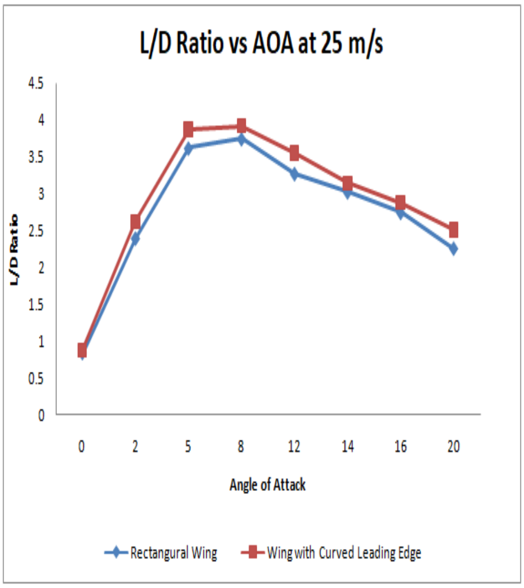


Fig. 4 Variation of lift to drag ratio(aerodynamic efficiency) with angles of attack

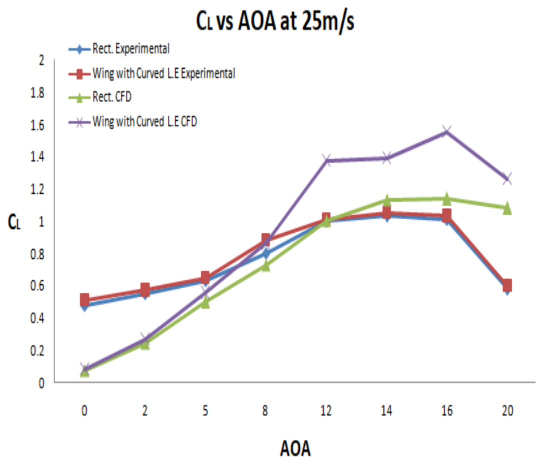


Fig. 5 Comparison of the coefficient of lift at various angles of attack

Fig. 5 shows comparative results of the coefficient of lift for rectangular and curved leading edge wing. From Fig. 5 it is clear that computational results have approximately the same trend as of experimental results of Haque and Ara 2015, except at low angles of attack because of wall effect at the starting of the flow in wind tunnel and due to viscosity considerations. Also it is observed that there is an increase in C_L values for the modified curved wing design when compared to the standard rectangular wing for each angle of attack.

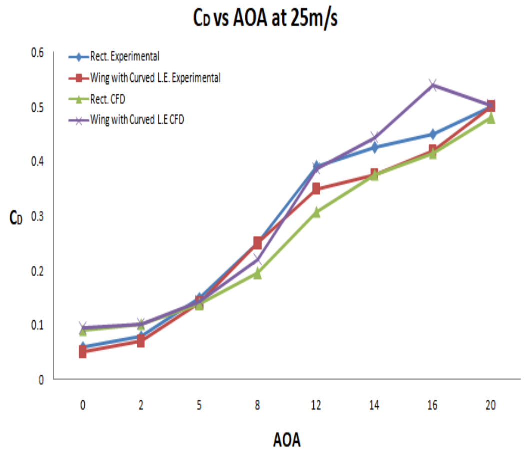
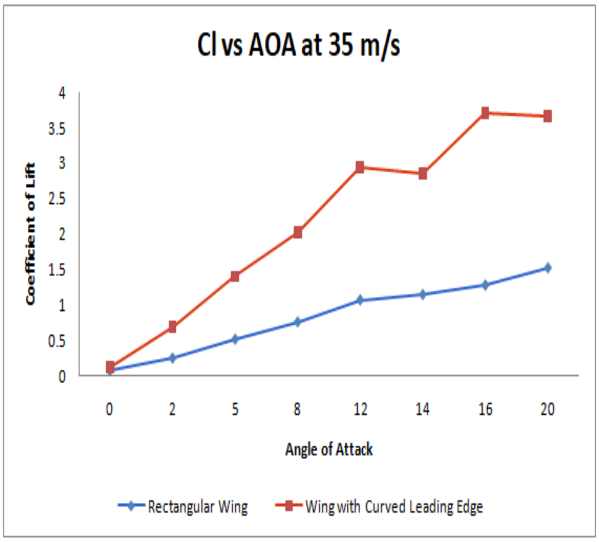
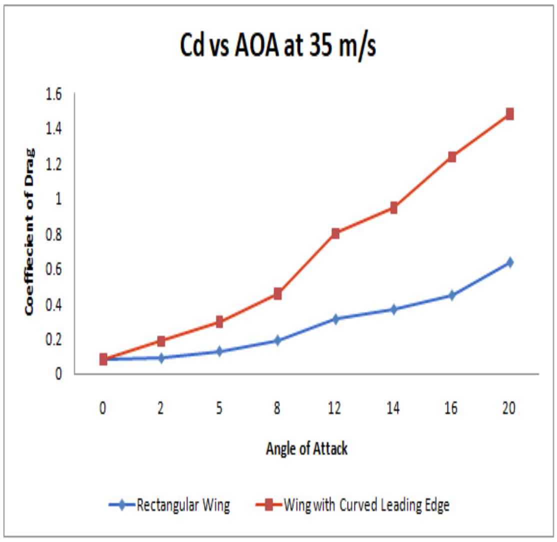


Fig. 6 Comparison of the coefficient of drag at various angles of attack



(a) C_L variation with angles of attack at 35 m/s



(b) C_D variation with angles of attack at 35 m/s

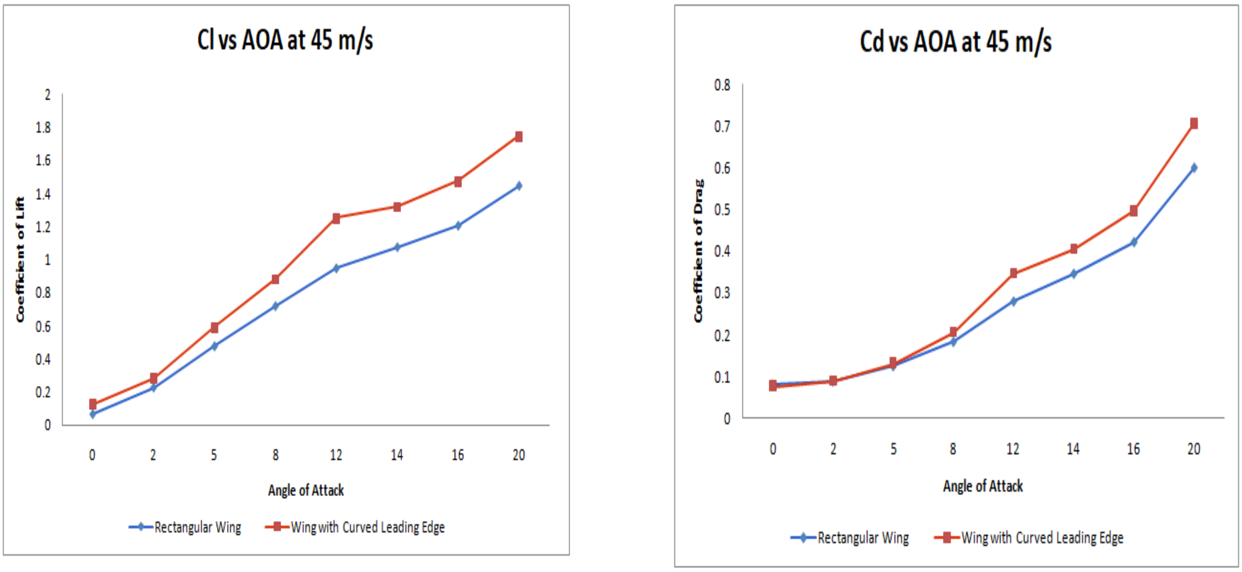
Fig. 7 Variation of C_L and C_D at various angles of attack

Fig. 6 shows the variation of the coefficient of drag with angles of attack. It is observed that the coefficient of drag for the curved wing below stalling point has a lower value than in comparison to the rectangular wing.

Fig. 7(a) shows the variation of coefficient of lift with angles of attack at 35 m/s and it is clearly visible that the wing with curved leading edge modification has maximum lift coefficient with an angle of stall near 12°. Fig. 7(b) shows the variation of drag force with angles of attack.

Fig. 8(a) shows the variation of coefficient of lift with angles of attack at 45 m/s and it is clearly visible that the wing with curved leading edge shows improved lift coefficient over the rectangular wing. Fig. 8(b) shows the variation of drag force with angles of attack. It is observed that the coefficient of drag for the curved wing below stalling point has a lower value than in comparison to the rectangular wing.

Fig. 9 shows the variation of the lift to drag ratio for various angles of attack. Initial values are diverging from the experimental values but once the flow is fully developed on the wings, the values are showing a very good agreement with the experimental results. This variation in initial aerodynamic efficiency values of the wing is due to the viscous effect of the airflow on the wing in experimental testing of a wind tunnel. Results show that curved leading edge modification to the wing improves the aerodynamic performance significantly. Proposed design modification may be incorporated in military fighter aircraft to improve their aerobatics maneuvers and stall characteristics.



(a) C_L variation with angles of attack at 35 m/s (b) C_D variation with angles of attack at 35 m/s

Fig. 8 Variation of C_L and C_D at various angles of attack

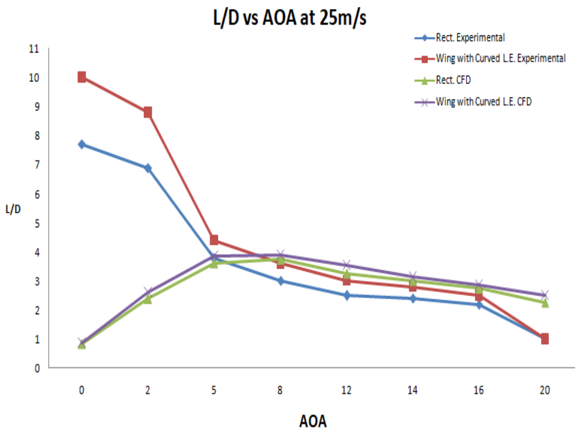


Fig. 9 Aerodynamic efficiency (L/D) variation with angles of attack

4. Conclusions

By taking a standard wing and providing a streamlined structure at the leading edge of the wing, the aerodynamic efficiency has increased significantly. Here a NACA 4412 airfoil was chosen for designing the wings. Then a comprehensive flow analysis is carried out using Ansys Fluent. The results were promising by showing a considerable increase in lift and lift to drag ratio for the aircraft wing.

- An analysis was run for a standard aircraft wing and compared with the experimental values as reported in the literature to find the errors. It can be concluded that the experimental and the results obtained from computational fluid dynamics (CFD) techniques are showing a closure agreement.
- Curved location is identified and leading-edge is designed as curved, which have shown better aerodynamic performances over its rectangular counterpart.
- Since the new wing design, i.e, the wing with a curved leading edge has better aerodynamic performance, these can be possibly applied to transport and military aircrafts design as it can reduce the fuel consumed by the aircraft significantly.

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