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Aerodynamic design optimization of an aircraft wing for drag reduction using computational fluid dynamics approach

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Abstract. The aircraft industry supports aviation by building aircraft and manufacturing aircraft parts for their maintenance. Fuel economization is one of the biggest concerns in the aircraft industry. The reduction in specific fuel consumption of aircraft can be achieved by a variety of means, simplest and more effective is the one to impose minor modifications in the aircraft main wing or the parts which are exposed to the air flow. This method can lead to a reduction in aerodynamic resistance offered by the air and have a smoother flight. The main objective of this study is to propose geometric design modifications on an existing aircraft wing which acts as a vortex generator and it can reduce the drag and increase lift to drag ratio, leading to lower fuel consumption. The NACA 2412 aircraft wing is modified and designed. Rigorous flow analysis is carried out using computational fluid dynamics based software Ansys Fluent. Results show that saw tooth modification to the main wing shows the best aerodynamic efficiency as compared to other modifications.

Keywords: aircraft industry; NACA; fuel economization; aerodynamic efficiency; ANSYS fluent

1. Introduction

The current trend in the aircraft industry is moving towards fuel conservation and economization due to the alarming rate at which fossil fuels are depleting and this has forced the aircraft industry to look for different strategies to reduce fuel consumption. Fuel economy is the energy efficiency in an aircraft and it is one of the critical parameters to assess aircraft performance. There is an urge in the improvement of aerodynamic design of aircraft due to the requirement to have an efficient aerodynamic performance to reduce fuel consumption, necessitates miscellaneous design adaptations. The aircraft's performance depends on various parameters, but the main wing design which is responsible for creating 90% of the total lift by aircraft plays a critical role (Okonkwo and Smith 2016).

The coefficient of lift, coefficient of drag, lift to drag ratio and stalling characteristics are considered during the selection of the wing for an aircraft. Implementation of active and passive design features that can control the flow over the wing have been proposed in several earlier studies and have shown efficient methods to increase the lift to drag ratio (Piedra et al. 2018, Nematollahi et al. 2019, Brüderlin et al. 2017, Aresti et al. 2013, Kim et al. 2016). Slats, flaps wing fences, and vortex generators are some of the design features that are already being used to improve the performance of aircraft wing. A vortex generator produces a stream-wise vortex that can mix the flow present near the upper surface with the layers above this where the flow moves at a faster velocity. This mixing of flows causes the velocity on the upper surface to increase which leads to a reduction in pressure and increase in lift. Passive flow controls are common in aircraft through the generation of flux vortices. There are various intriguing methods which serve in vortex generation. The saw-tooth leading edge and leading-edge strake as shown in Fig. 1(a) and Fig. 1(b) respectively are a few common methods for generating powerful stream-wise vortex. The basic principle is to produce an array of small stream-wise vortices that facilitate enhanced mixing of high-speed air in the main stream with the relatively low-speed nearer the surface (Kundu et al. 2016). The boundary layer is re-energized in this way. The vortex generators mentioned above promote the reattachment of separate boundary layers within the separation bubbles, which postpone the fully developed stall. In addition, these fixed vortex generators are simple, cheap and robust Various ideologies have been already implemented in order to enhance the aerodynamic performance of aircraft by optimizing the various components and design parameters influencing the performance (Unchai and Janyalertadun 2014, Ozmen 2013, Ravi Kumar B. 2019, Kumar and Saranprabhu 2018, Hyams et al. 2011, Kurec et al. 2019, Saranprabhu et al. 2017). (Booma Devi and Shah 2017) have studied the usage of supplementary vortex generators to modify the tip vortex from a half-span aerofoil. The experiment was conducted using LaVision Flowmaster PIV which showed that the triangular generators were the best as they produced substantial vortex enlargement with low lift penalty.

Nematollahi et al. 2019 carried out aerodynamic performance and flow characteristics of a delta wing with coarse axial riblets and compared it with a smooth-delta wing. The flow was visualized using Particle Image velocimetry for the wing at six cross-sections and various

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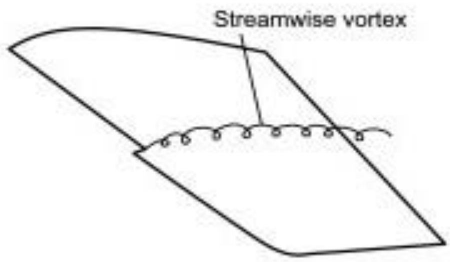
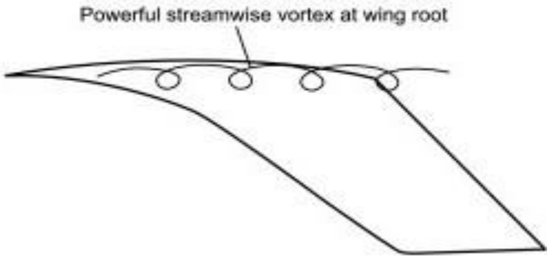


(a) Saw-tooth leading edge



(b) Leading edge strake

Fig. 1 Passive vortex generators (Houghton et al. 2012)

other constraints. The analysis was carried out using constraints obtained by Q-criterion. The results reported that the proposed model had a positive effect on some of the parameters related to drag reduction and increased lift. An increase in flow momentum was also observed near the upper wing and behind the wing. (Brüderlin et al. 2017) carried the study of effectiveness of a winglet control system through vortex generators using RANS simulation. Various range of flow conditions and deflection angles were considered and the RANS equation was solved using TAU solver. Ansys is used to carry out the simulation and further analysis. The results reported that an increase in lift can be observed by using winglet designs. (Nangia et al. 2019) assessed the aerodynamic design of a UCAV wing which was developed under the NATO-STO AVT-251. The baseline and designed wings were analysed using several Navier-Stokes computational fluid dynamics flow solver. Cobalt Version 7 was used to carry out the DSTL calculations. RANS equation was solved using SARC turbulence model. The results provide that there would be additional lift available to maneuver with minor modifications on the wing structure.

Piedra et al. 2018 reported a study in which the aerodynamic study was carried out in conjunction with ASTM F2245 and COAV 27/12 to comply with the flight requirements of the new sport aircraft. A comprehensive simulation was conducted using Ansys Fluent.

In the present study, vortex generators based modifications at the leading edge – saw-tooth and leading-edge strake are designed on NACA 2412 aircraft wing using SolidWorks. Three models of saw-tooth leading edge and two-models of leading edge strake are designed and analysed using standard k-epsilon model to get aerodynamic characteristics. The results are compared with that of a basic NACA 2412 rectangular wing for various speeds and angle of attacks. A significant improvement in aerodynamic efficiency is observed in saw-toothed leading edge wing as compared to base wing and wing with leading edge strake design.

2. Wing design

The primary step of the study is designing and developing a model of the aircraft wing. NACA 2412 airfoil is used as the base airfoil to design the aircraft wing using SolidWorks software. The base model is a rectangular aircraft wing of span 660 mm and a chord length of 330 mm as shown in Fig. 2(a).

The base model was used as the foundation for the development of the proposed saw tooth and strake modifications. The length of the cut is altered in each sub-cases of the saw-tooth models. The different cut of 165 mm, 265 mm, and 330mm are chosen as the variation in each sub-cases from the wing root as shown in Fig. 2(b), Fig. 2(c) and Fig. 2(d) respectively.

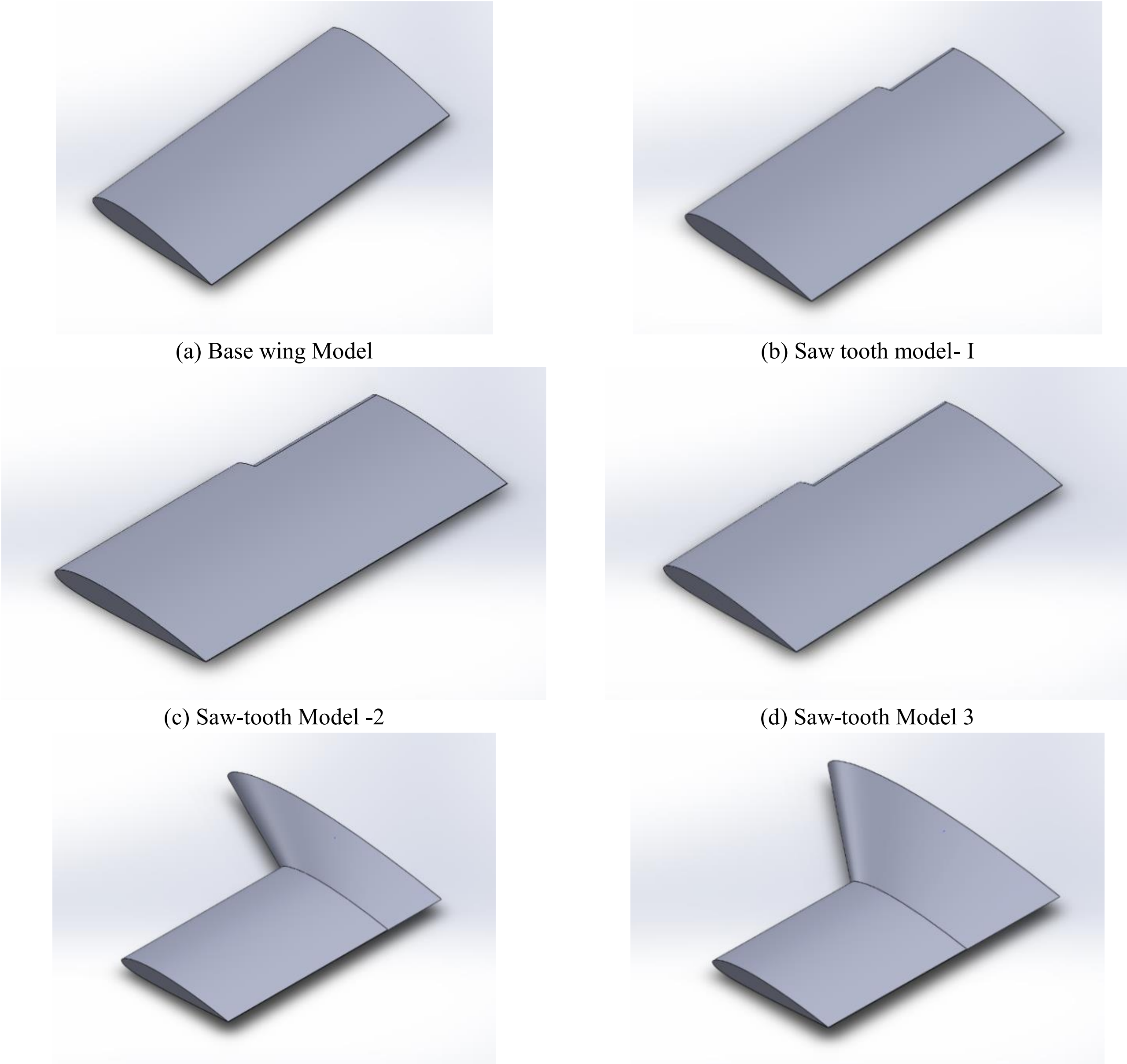
The strake models were constructed by using extrude and lofted boss tools in SolidWorks. The maximum chord length is 660 mm which is present near the root while the minimum chord length is 330 mm at the tip. The span of the strake is varied to obtain the two models. In the first model, the span of the strake is 165mm as shown in Fig. 2(e) and in the second model, the span of the strake is 265mm as shown in Fig. 2(f).

3. Computational and flow analysis

The models which were designed are processed for computational analysis using ANSYS Fluent. The models created in SolidWorks were converted to IGES format and then imported to ANSYS to perform meshing and simulation. The computational domain is generated in design modeler by constructing a cuboid of the same thickness of that of a wing span of 660mm around the wing. The flow field is about 5 times the chord length in the front, top, and bottom of the wing and 10 times the chord length behind the wing.

3.1 Meshing and mesh sensitivity analysis

The mesh sensitivity study is performed on the base model by increasing the number of elements in a domain and analyzing the coefficient of lift for each mesh. The element size is reduced to increase the number of elements. The inflation layer is constrained to a total thickness of 0.3m for all the domains. The study was conducted at 2 m/s inlet velocity and zero degree angle of attack. The analysis was repeated until the coefficient of lift was found to be within the variation of 2 to 3 percent. From table 1 it is observed that the number of elements for the converged results is to be about 112631. All the models meshed with their respective element sizes so that the overall element count for each model falls in between the limiting count and meshed models are shown in Fig. 3.



(a) Base wing Model (b) Saw tooth model- I

(c) Saw-tooth Model -2 (d) Saw-tooth Model 3

(e) Strake Model 1 (f) Strake Model 2

Fig. 2 Aircraft wing base model and models with the proposed design modifications

Table 1 Mesh sensitivity analysis

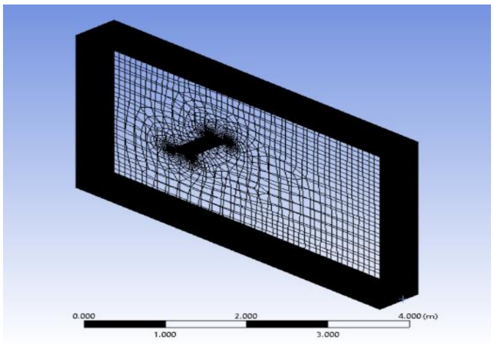
Element size (m)	Coefficient of Lift	No. of elements	No. of nodes
0.3	0.10880262	46170	49542
0.28	0.10767812	50692	54285
0.26	0.11105021	72695	77588
0.24	0.10352972	81060	86336
0.22	0.10591213	89392	95250
0.2	0.11197889	95784	102542
0.18	0.11151419	112631	120456
0.16	0.10972139	142208	151211

4. Results and discussion

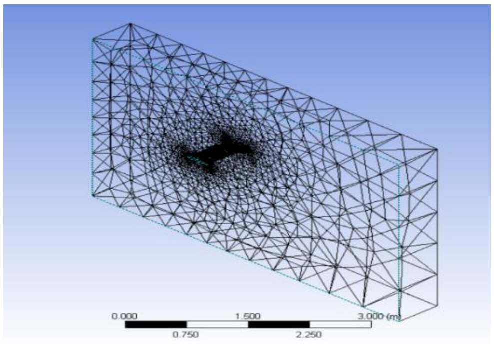
The flow analysis was performed in ANSYS fluent solver using the standard k-epsilon model as the turbulence model for the flow. The inlet boundary condition is specified as velocity-inlet and the outlet condition is specified as pressure-outlet. The analysis is performed for 0^o, 5^o, 10^o, 12^o, 14^o, 16^o, and 18^o angle of attack. For each angle of attack, various inlet velocities of 2 m/s, 10 m/s, 20 m/s, and 40 m/s were considered for simulation. The coefficient of lift, coefficient of drag and aerodynamic efficiency were obtained for each configuration and presented.

4.1 Base model wing characteristics curves

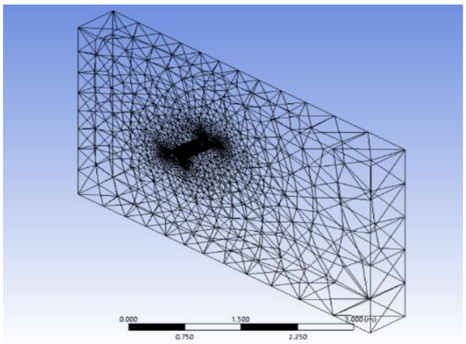
The values obtained from the analysis show that the maximum value of coefficient of lift for the base model was 0.578681 at 40m/s and that also coincides with the maximum value of coefficient of lift at 20 m/s at a



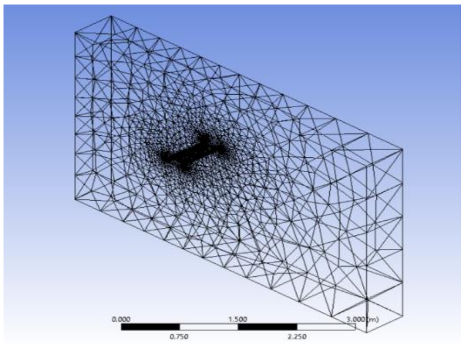
(a) Base Model



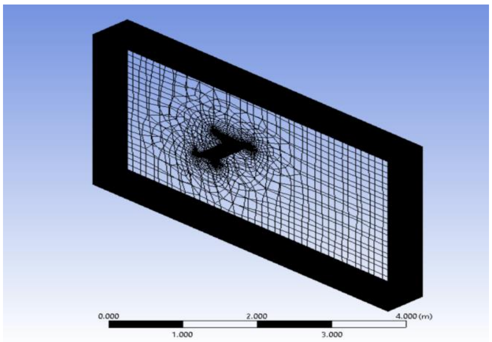
(b) Saw-tooth Model 1



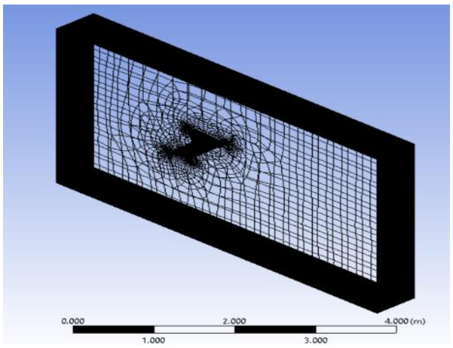
(c) Saw-tooth Model 2



(d) Saw-tooth Model 3

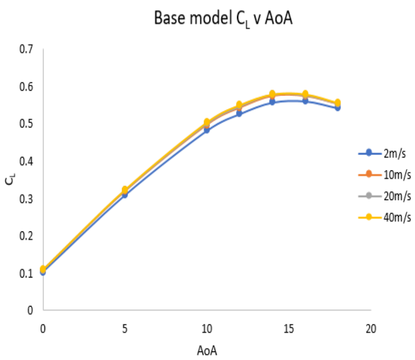


(d) Strake Model 1

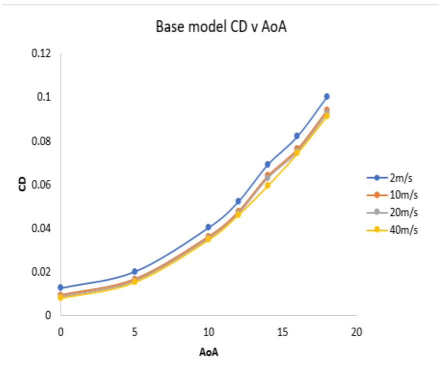


(e) Strake Model 2

Fig. 3 Meshed wing base model and models with modification



(a) Coefficient of lift vs Angle of attack

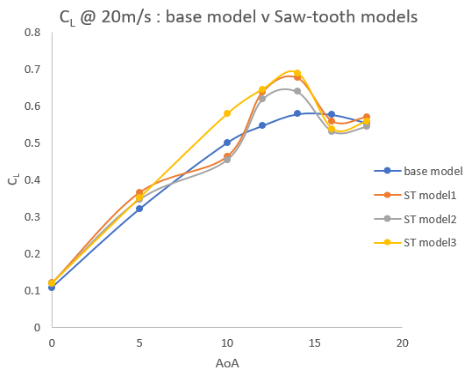


(b) Coefficient of drag vs Angle of attack

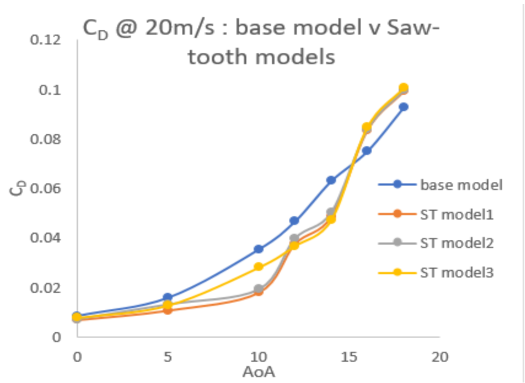
Fig. 4 Aerodynamic performance of the Base model wing

corresponding angle of attack 14.5°. Fig. 4(a) shows the variation lift with angle of attack at various velocities and Fig. 4(b) shows the variation of drag on base aircraft wing.

As the velocity of the aircraft increases the drag also increases, the least drag is observed at 20 m/s for all angles of attack. Stalling on the wing is observed at about 15° angle of attack and beyond which drag increases abruptly.

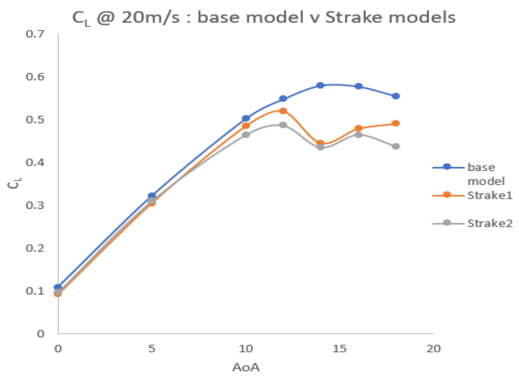


(a) C_L Variation with angle of attack

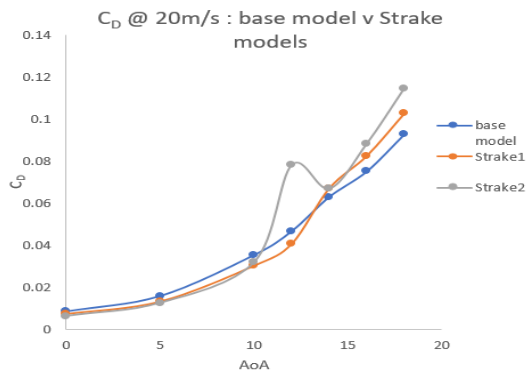


(b) C_D variation with angle of attack

Fig. 5. Aerodynamic performance of Base wing and wing with saw-tooth



(a) C_L Variation with angle of attack



(b) C_D variation with angle of attack

Fig. 6. Aerodynamic performance of Base wing and wing with leading edge strake

4.2 Comparison of the aerodynamic performance of base model with saw-tooth modification

Two types of saw-tooth modifications on the leading edge of the main wing were implemented and the results of the base model wing performances at 20 m/s are compared with the saw-tooth modifications. The best aerodynamic performance of the base wing is observed at 20 m/s at all angles of attack.

Fig. 5(a) presents the variation of lift with angle of attack for the base wing and for wing with saw-tooth modifications. It is clear that saw-tooth modification on the base wing has a strong influence on the aerodynamic performance. The presence of the saw-tooth at the leading edge of the wing enhances the turbulences on the top surface of the wing and the net effect is similar to that of the vortex generators. As a result of which there is a visible increment in lift and drag decreases significantly in the pre-stall region. The maximum lift coefficient is found to be 0.69 in the saw-tooth modification as compared with 0.57 of the base wing.

From Fig. 5(b) it is clearly visible that saw tooth modification shows the least drag over a wide range of angles of attack as compared to the base wing. If we compare the pre-stall and post-stall region of the flow, the performances of wing with saw-tooth modifications are superiors to that the base wing. At angle of attack near 10° flow gets re-energize due to enhanced vortices which can be viewed clearly in Fig. 5(a), this effect leads to enhancement in the maximum value of coefficient of lift and shows minimal drag (see Fig. 5(b)) compared to the main base wing.

4.3 Comparison of the aerodynamic performance of base model with strake modification

Two types of strake modifications on the leading edge of the main wing are implemented. The results of the base model wing performances at 20 m/s are compared with the saw-tooth modifications.

Fig. 6(a) shows the variation of lift with angle of attack for the base wing and for wing with leading edge strake modifications. It is observed that leading edge strake modifications on the base wing are not effective with regard to the aerodynamic performance and hence are not recommended for cruising flights. From Fig. 6(b) it is clearly visible that wing with leading edge strake shows low drag at moderate angles of attack (angle of attack from 0 to 10°) as compared to the base wing. Leading edge strake can be used during takeoff of the aircraft as it shows low drag at low angles but these are not beneficial at high speeds and high angles of attack.

4.4 Comparison of aerodynamic efficiency for base wing with saw-tooth wing

The aerodynamic efficiency of the base wing with the saw-toothed wings was compared at 20 m/s and it was observed that wing with saw-toot modification have shown

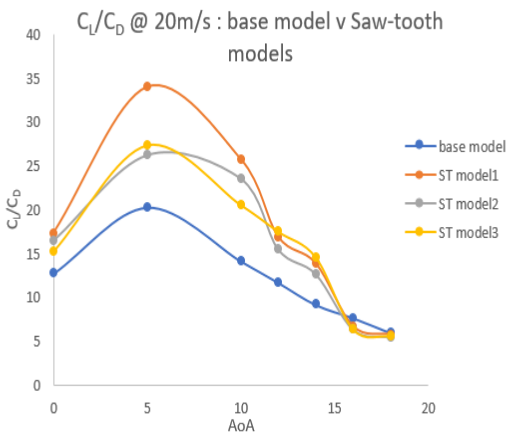


Fig. 7 Aerodynamic efficiency (L/D) variation with angle of attack

superior performances over a wide range of angles of attack as compared to the base wing. The maximum value of lift to drag ratio for the saw-tooth wing was observed to be 33.9864 as compared to 16.5 of the base wing.

5. Conclusions

In this work, the NACA 2412 aircraft wing is designed and implemented by techniques based on vortex generators such as a saw-tooth and leading-edge strake. Three models of saw-tooth and two-models of leading edge strake are designed and analysed via computational fluid dynamic based solver ANSYS Fluent using standard k-epsilon model to get aerodynamic characteristics. The results are compared with that of a basic NACA 2412 rectangular wing for various speeds and angle of attacks. From the results, it can be concluded that the wing with saw-tooth modification has the best aerodynamic performances over other modifications. Leading edge strake can be used during takeoff of the aircraft as it has shown low drag at low angles but these are not beneficial at high speeds and high angles of attack.

As we have proposed minor modifications to the existing aircraft wing, it can be implemented to modern fighter aircraft for enhancing its aerobatics and maneuverability.

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