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Edge Blending to Enhance the Flow Over Double delta wing configuration during re-entry

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Abstract. During re-entry of space vehicle, the vehicle undergoes flow variation from hypersonic flow to subsonic flow, which causes huge heat transfer over the wing configuration. The double delta wing of configuration 76 degree - 40 degree is considered and effect of blending the wing at edges showed variation and enhancement of flow over the double delta wing configuration. Heat flux calculations were carried out at regions of shock- shock interactions and the effect of blend radius at edges were analyzed using simulations done in ANSYS Fluent. It was observed that aerodynamic efficiency increases with the edge blending which ultimately enhanced the flow field over the double delta wing.
Keywords. Double Delta Wings, Blended Wing, Re-entry Condition, Flow Enhancement

1. Introduction

During an aircraft design, selection of wing is one of the most important parameter that is to be taken into consideration. Wings are designed in taking into parameters that directly impact on the whole aircraft. These parameters include the lift force generation, fuel storage considerations, angle of attack, lift angle and maneuverability stall angle. A delta wing has greater advantages than other types of wings and are used in fighter planes and spaceship applications where the flow is either supersonic or hypersonic flows [1,2]. A delta wing sweeps sharply from the fuselage with an angle between the leading edge of the wing often high as 60 degrees and the angle between the fuselage and the trailing edge of the wing mostly around 90 degrees [3]. A double delta wing is essentially a wing with a kink in its leading edges that forms the support wherein the leading edge of the strake and main wing intersect.

Table 1. Nomenclature

Symbols	Description
α, φ	Angle of attack [deg]
δe	Elevon deflection angle [deg]
θ	Bent angle [deg]
$(C_D)_v$	Vortex Drag coefficient [n.d]
$(C_L)_v$	Vortex Lift coefficient [n.d] L
C_D	Drag coefficient [n.d]
C_L	Lift coefficient [n.d]
C_{Mx}	Rolling moment coefficient [n.d]
C_{My}	Pitching moment coefficient [n.d]
C_{Mz}	Yawing moment coefficient [n.d]

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C_M	Pitching moment coefficient [n.d]
$C_{M\alpha}$	Pitching moment derivative [n.d]
C_N	Normal force coefficient [n.d]
C_Y	Side force coefficient [n.d]
h	Total height of vehicle cabin [m]
h_{ws}	Half-width of vehicle cabin [m]
l_t	Total length of vehicle [m]
l_{ref}	Wing mean aerodynamic chord [m]
M_∞ , M_o	Mach number [n.d]
m_{tot}	Total mass of the vehicle (TPS included) [kg]
r_n	Nose radius [m]
S_{ref}	Aeroshape planform area [m^2]
V_∞	Free-stream velocity [m/s]
V_{max}	Maximum landing speed [m/s]

2. Double delta wings

At the front end of the main wing, double delta wing has leading edge extensions, also called as strakes. These strakes have a higher swept angle in order to achieve vortex stability. Most importantly, the configurations that needed to be taken into consideration on double delta wing so as to achieve sufficient supersonic cruise performance is the sweep angle combination [3]. A monolithic wing body configuration with double delta wing having quite high sweep angle becomes more advantageous as it lowers the heat fluxes over the leading edge [4].

Investigations are carried out during the re-entry condition of vehicle. During re-entry of vehicle the vehicle experiences the flow change from supersonic to transonic then to subsonic flow. Previous study prevails that there must be improvisation of performance at low speed in order to achieve a safe horizontal landing. Moreover, safety is one of the important parameter to be considered [4].

Numerous study have been carried out on double delta wing and re-entry of vehicle. Antonio Viviani, Andrea Aprovitola, Luigi Iuspa and Giuseppe Pezzella [4] evaluated the low speed longitudinal aerodynamic performance of spacecraft which has a blended wing body aeroshape with unconventionality. The authors showed using body flap enhances longitudinal static stability, provides side slip control and also gives lateral directional manoeuvrability. To obtain high speed as well as low speed design requirements, multi-disciplinary design optimization (MDO) has been applied. Analytical results were compared with simulations keeping the spacecraft at low Mach number, it concluded that behaviour at landing angle of attack (AoA) exhibits the initializing and improvement of two vortex system which helps in vortex lift and thereby increases the lift coefficient. It drawbacks at ability for landing horizontally and also reduction of aerodynamic efficiency of 25%.

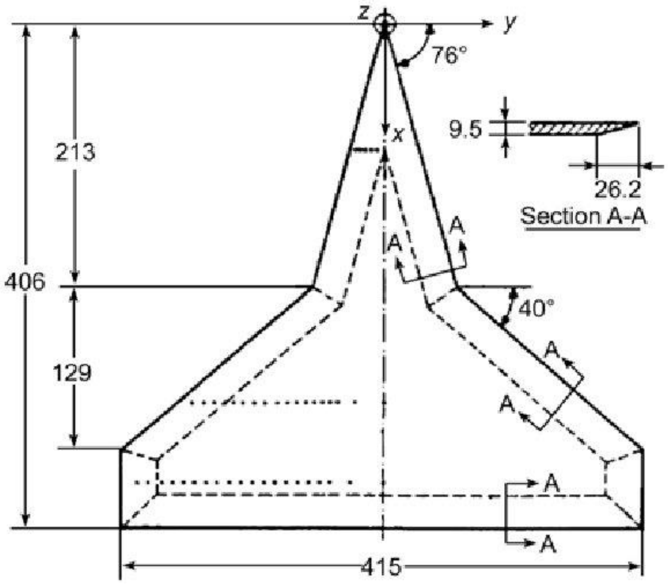


Figure 1. $76^0 - 40^0$ Double Delta Wing [10]

Gaoxiang, Chun, Honghui and Zonglin describes the Shock- Shock Interactions between the body and wings at supersonic flows with a wing considered as sharp wing and body as flat wedge [5]. The thermal protection of aircraft and design specifications are also detailed in their research. Wedge angle greatly affects the wave configuration as compared to swept angle. The flow structures were solved by flow dynamics, finding the geometrical relationships between the 3-dimensional steady and 2-dimensional unsteady problem with decomposed Mach numbers properly described in sections, the steady problem is considered as interactions of two incident waves, succeeding over the characteristic plane; for unsteady problem shock polar analysis was done [5].

P.R Vishwanath has investigated that skin friction drag reduction can be done by the use of riblets [6]. Riblets are micro-grooves that are applied over the surface in accordance with freestream direction. The author reviewed the performance of riblet when applied over the airfoil wings and wing- body configuration at varying speed. To determine the viscous drag reduction from riblets, three different methods were applied; the first approach is skin friction balance to directly measure the wall shear stress; the second approach is 2D boundary layer momentum integral [MI] and third approach is internal strain gauge balance [6]. Mohammad Ghalandari, Ibhrahim Mahariq, Farad Ghadak and Fahad Jarad described briefly the aileron mass parameter has an adverse effect on velocity and frequency of flutter issues [7]. Fluttering is the self-vibrations occurring at varying speeds, is considered to be most common problem, which can ultimately lead to structure failure if proper damping system is absent. The authors have applied the multi-disciplinary design optimization (MDO) technique [4] in order to achieve flutter wing analysis and optimization. The position and centre of mass are effective and no need to unify the mass moment of inertia. The MDO helped to investigate the best position for aileron of composite wing. The present work describes the flow over the double delta wing at re-entry condition, the variation of flow from supersonic to subsonic and the aerodynamic performance study over the wing is considered. Also the effect of edge blending to enhance the flow is done and simulations were done with help of ANSYS Fluent. The values of drag coefficient, lift coefficient and moment coefficient obtained from simulations are plotted against angle of attack. The values are compared with values obtained from Slender Wing Theory.

3. Numerical Methods

Considering the slender wing theory to obtain the relation between the drag & pressure coefficient along with lift coefficient at high angle of attack the following relations given by the theory:

$$(C_L)_p = \frac{\pi AR}{2} \sin\alpha \cos\alpha \qquad (1)$$

$$(C_L)_p = (C_L)_P \sin\alpha \qquad (2)$$

Then, the following vortex (v) lift terms:

$$(C_L)_V = (C_D)_{pf} \sin^2\alpha \cos\alpha \qquad (3)$$

$$(C_L)_V = (C_D)_{pf} \sin^3\alpha \qquad (4)$$

As a result, lift and drag coefficients become:

$$(C_L) = (C_L)_p + (C_L)_V = \frac{\pi AR}{2} \sin\alpha \cos\alpha + (C_D)_{pf} \sin^2\alpha \cos\alpha$$

$$(C_D)_p = (C_D)_p + (C_D)_V = \frac{\pi AR}{2} \sin^2\alpha \cos\alpha + (C_D)_{pf} \sin^3\alpha$$

Four main parameters that affect the wing configuration are the pressure or thrust, lift force, drag force and weight and shape of wing and body. Slender wing theory explains briefly the actual conditions that will be worked out at the peripheral of delta and double delta wings which gives the findings of aerodynamic parameters like relation of drag and lift coefficient along with angle of attack.

Now as to calculate the heat flux over the regions, basic numerical study and aerodynamic relations are to be considered as given [8]:-

$$To/T = 1+((\gamma-1)/2) * M^2 \qquad (5)$$

This will give the static temperature. Now further to find speed of object and speed of sound we use the below empirical relationships

$$\text{Velocity of Sound} = a = (YRT)^{1/2} \qquad (6)$$

and

$$\text{Mach number} = M = C/a = \text{Object Speed / Speed of Sound} \qquad (7)$$

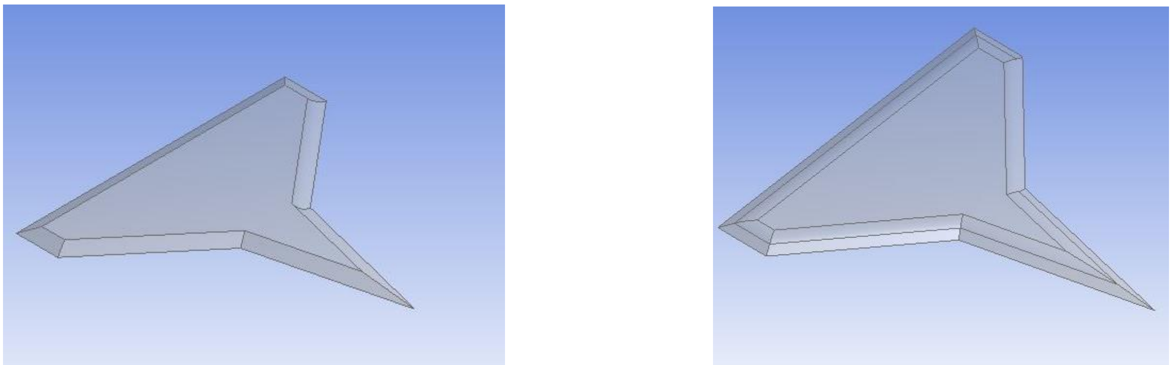
Shock-shock interactions are considered for investigating the aerodynamic heating of wings, initial methods were to use the basic relations of pressure and heat in order to obtain aerodynamic heating but not applicable to complex geometry [5]. To obtain the flow deflections, the below relation is used from the oblique- shock interactions that is given by L. Laguarda [6] in its research as :-

$$\nu^i_{km} = f(M_0, \varphi, \gamma)$$

$$= \tan^{-1}[((2*(M^i_0 * \sin\varphi^i_{km})^2 - 1) / (Mi_0^2(\gamma + \cos 2\varphi^i_{km}) + 2) * \tan\varphi^i_{km})] \qquad (8)$$

Where specific heat ratio is taken as 1.4.

Aerodynamic investigation was carried out with initial design of double delta wing [1] without giving blend radius at the edges and angle of attack given with enclosure created along with the tetrahedral meshing with mesh refinement over the wing, importing and solving the three dimensional RANS equation, considering the density based solver and enabling the energy equation; using the k-omega SST model; as flow is compressible and is computed using the ANSYS Fluent. Air is considered as perfect gas with density kept as ideal- gas and viscosity to be given as accordance to Sutherland's Law, thermal conductivity is kept at *0.0242W/mK* and the specific heat (at constant pressure) to be *1.006 kJ/kgK.* Boundary conditions were kept as inlet to be as pressure far-field giving initial Mach number to be 0.6 as considering the flow to be subsonic flow. Respective gauge pressure and temperature is given at inlet; the wall is kept at adiabatic condition and outlet to be pressure outlet with standard boundary conditions. The convergence condition was kept at decimal of 0.001. Convective fluxes were discretized using second order- Roe Flux Difference Splitting (FDS); while diffusive fluxes are discretized by considering a cell-centred scheme. The Courant Number (CN) is automatically numbered by the Solution Steering (SS) algorithm in Fluent wherein the flow can be kept as per our required conditions; moreover, the hybrid initialization is done because it uses the boundary conditions then solves the Euler problem and uses the solution to Euler problem as initial guess. Further keeping the same input condition, the wing was edge- blended and the simulations were carried out with all boundary conditions keeping same.



a) Double delta wing b) Double delta wing (edge blend)

Figure 2. Double Delta Wing (with edge blending)

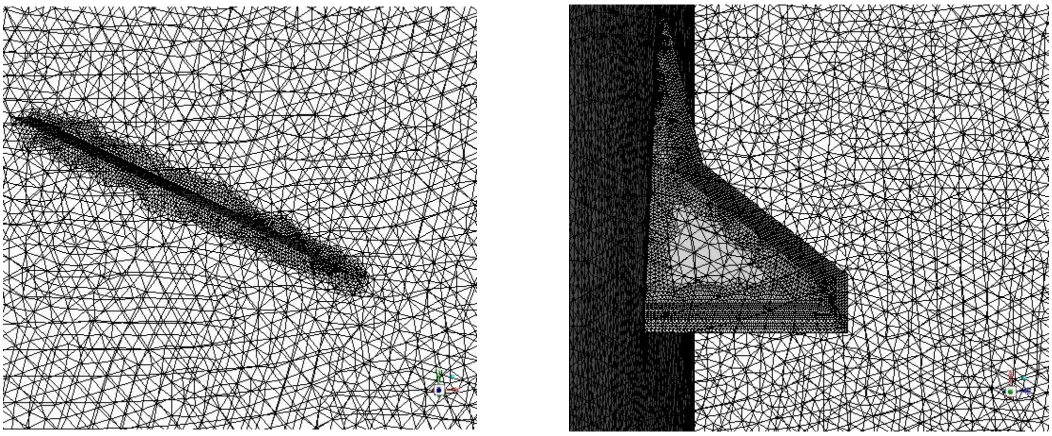


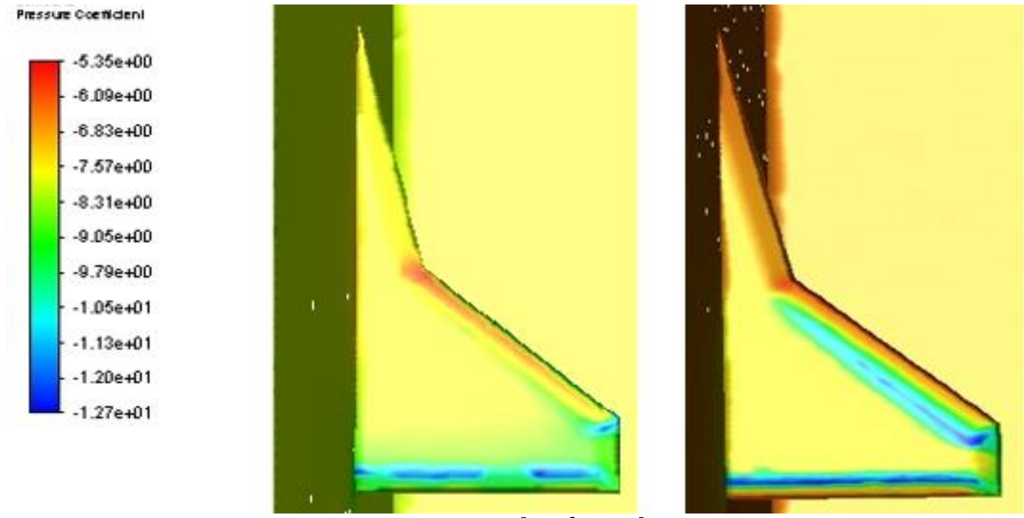
Figure 3. Meshing

4. Results

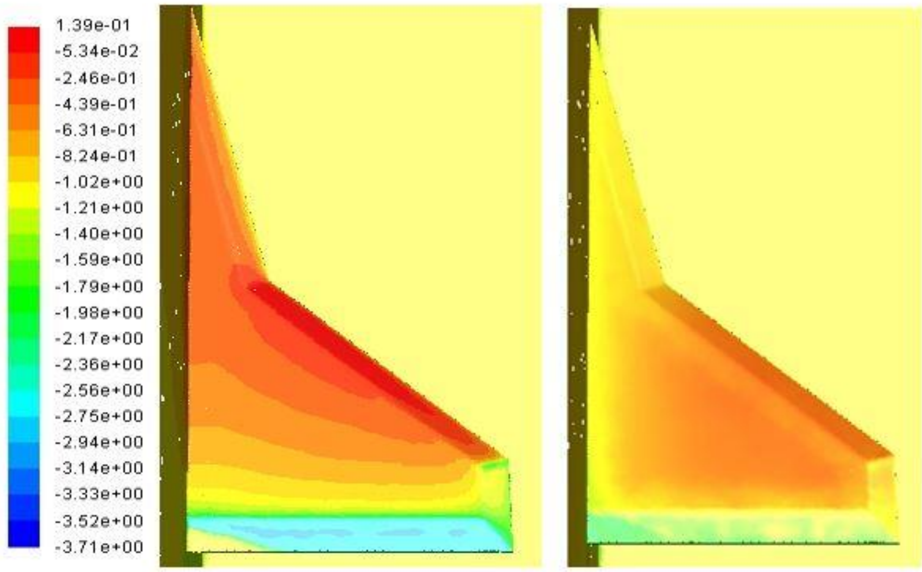
The results showed that by blending it by radius of 0.03m and increasing it to certain level, it was observed that the flow over the wing has enhanced that can be seen in pressure contour diagram.

The figures showed the simulations over the double delta wing at different angle of attack, the left shows the wing without blend and the right shows the pressure contour over the wing with edge blending. It can be observed that the blended wing helps in reducing the creation of spots over which the pressure gets debated. The values of drag, lift and moment coefficient were obtained, which was compared with Slender Wing theory**.**

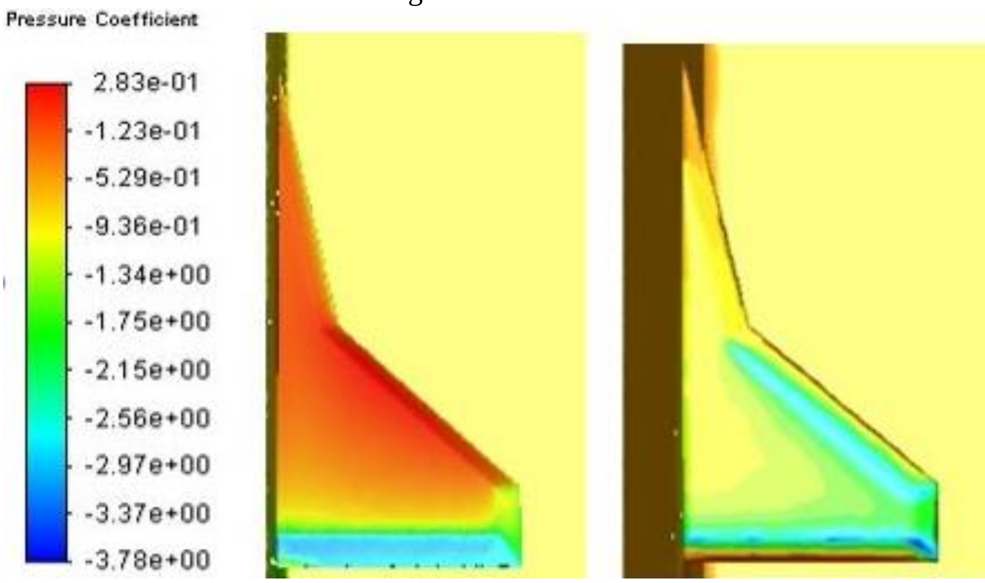
The graphs were plotted with previous research data and were compared with the obtained results of edge blending. It was observed that the lift coefficient increases and drag coefficient decreases when edge blending is done, this exhibits that the flow has improvised over the wing since drag reduction causes friction to be emerged at lower value thereby increasing the smooth flow over the wing. Moreover, the lift to drag ratio increases which leads to increase in efficiency of aircraft. It was also observed that as angle of attack increases there is an increase in drag and lift to drag ratio tends to decrease. The maximum lift to drag occurs at initial 5^0 angle of attack during re-entry of spacecraft into the Earth's Orbit.



Angle of attack = 5°



Angle of attack = 25°



Angle of attack = 35°

Figure 4. Pressure Contours at different angle of attack (left: without blend; right: with edge blending)

The figure 5 describes the variation of drag coefficient with angle of attack, it was observed that at initial 5^0 angle of attack drag coefficient gets reduced as edge of wing is blended, thereby reducing the vortex generation at the end tips. But as angle of attack increases there is no much huge effect of blend as can be seen at angle of attack 45^0. The figure 6 describes the lift coefficient plotted against the angle of attack given, it was observed that lift coefficient increases at lower angle of attack for the blended wing, but at angle of attack at 45^0 the values seems to be almost same for normal and blended wing.

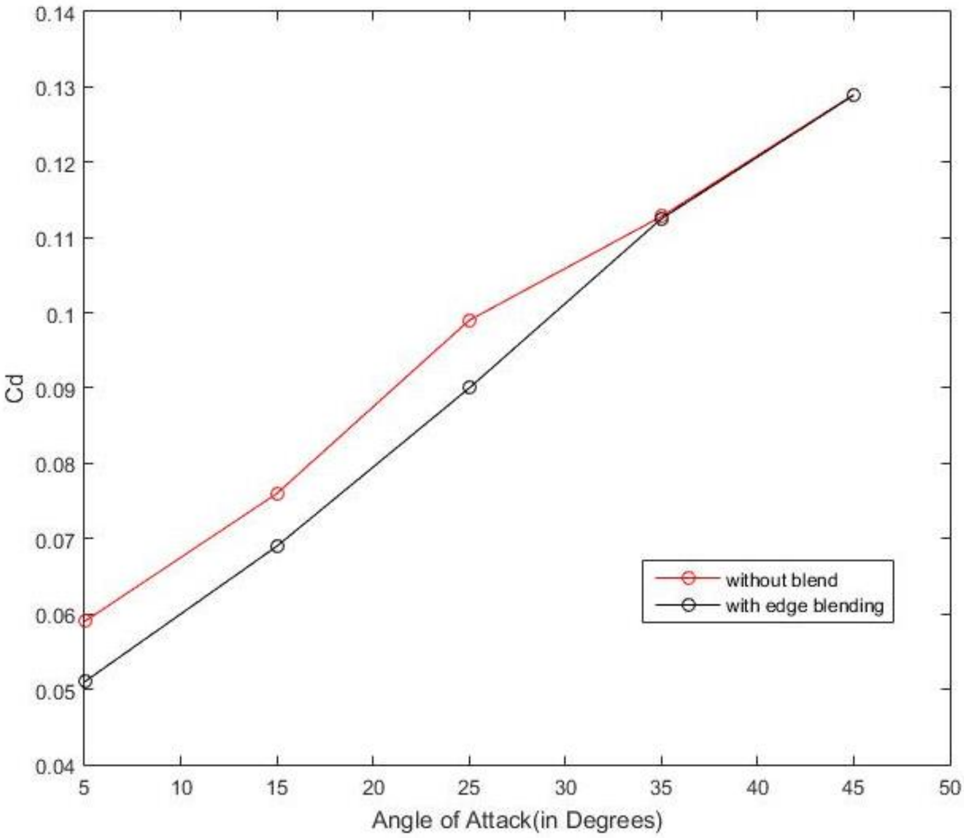


Figure 5. C_D v/s Angle of Attack

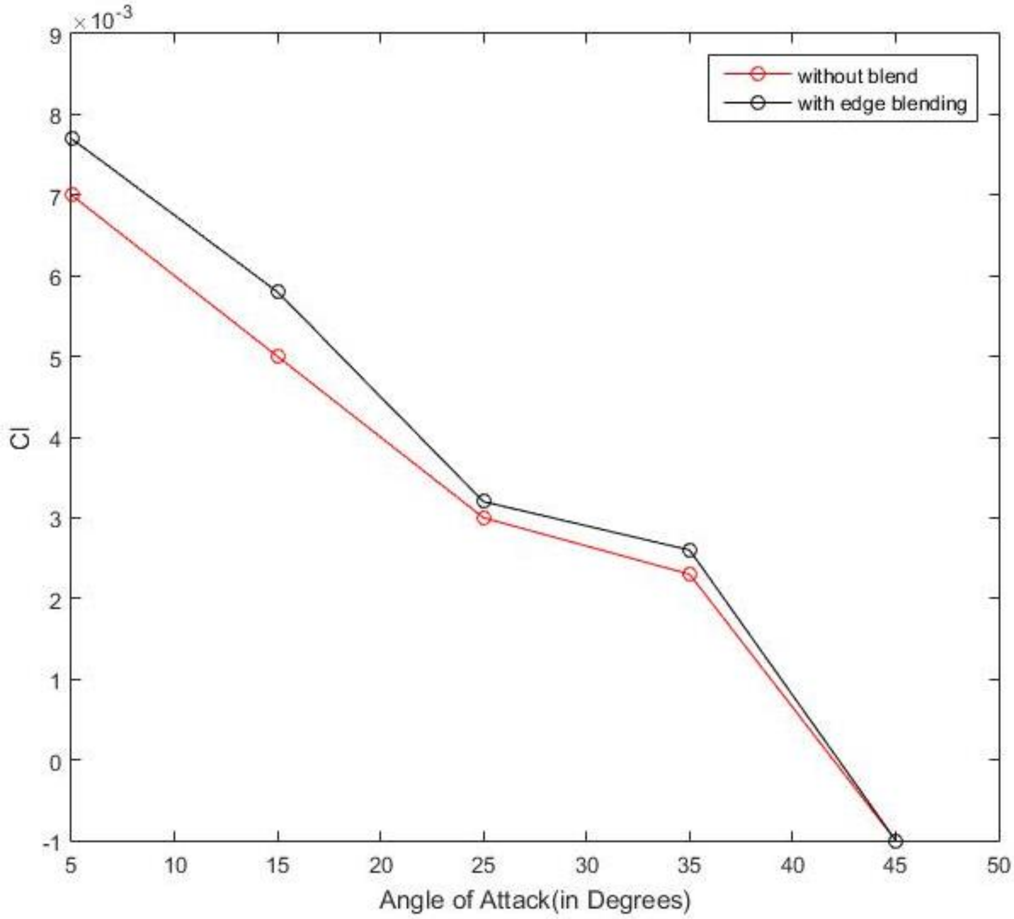


Figure 6. C_L v/s Angle of Attack

The figure 7 explains the lift to drag ratio versus the angle of attack and it can be thereby observed that the lift to drag ratio is much higher in case of blended wing as compared to normal double delta wing, the double delta wing with blend satisfies the subsonic re-entry conditions, with giving greater ability to accelerate and stabilize the wing since the flow gets enhanced as ratio increases. Moreover, the lift coefficient curve shows the non-linearity as it was expected.

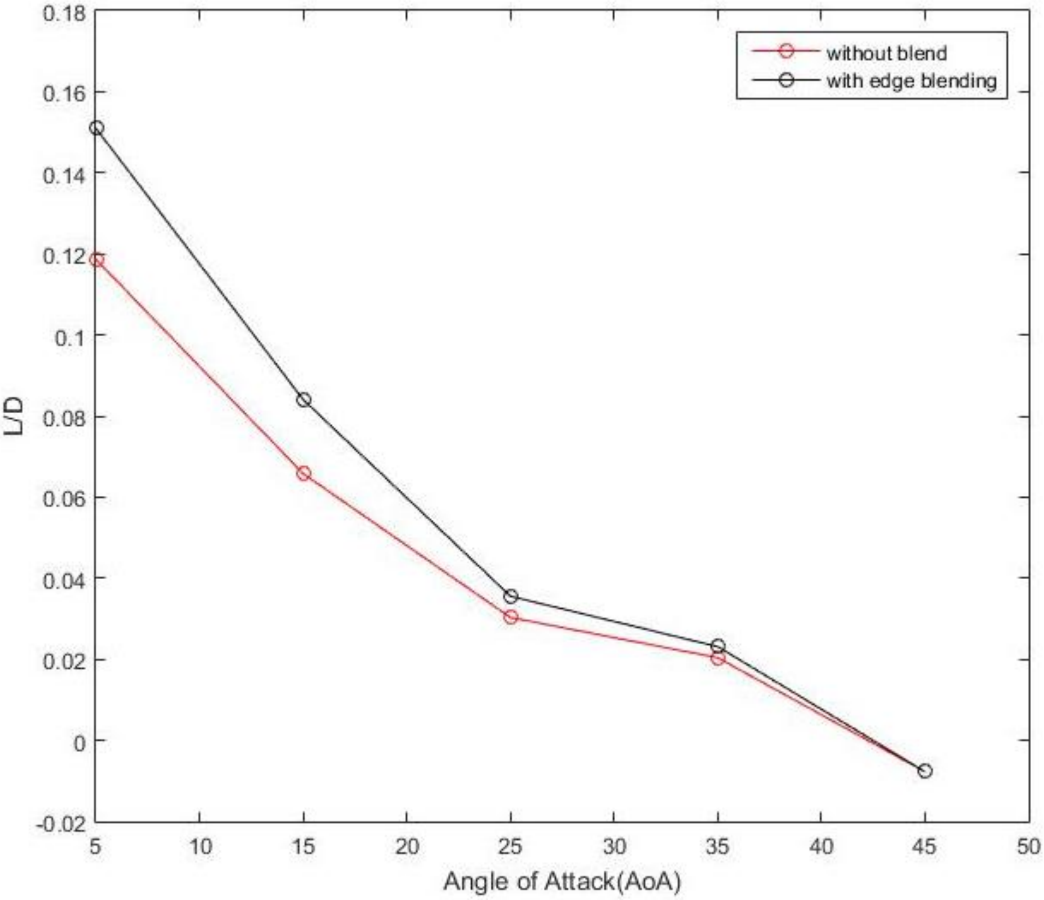


Figure 7. L/D v/s angle of attack

5. Conclusion

The edge blending exhibits greater aerodynamic efficiency as compared to normal $76^0 – 40^0$ double delta wing but limits at higher angle of attack from 45^0. The blended wing increases the stability and since the lower the drag and higher the lift more is the stability of wing. The pressure contours moreover show that the wing experiences lower pressure thereby enhancing the flow since it also cools the wing at the edges. The simulations were carried out considering the proper wind tunnel conditions and as per standard conditions the blended wing and the normal wing were simulated and the results were compared with previous research work, the blend concept showed greater advantages as compared to previous work.

Declaration of competing interest. The authors declare that they have no competing financial interest or personal relationship that could have influenced the paper.

CRediT authorship contribution statement.

Krishna Jaiswal: Conceptualization, Methodology, Analytic Calculations, Problem analysis, Investigation, Simulation, Writing- Original Draft.

Pratik Ganorkar: Investigation, Problem Defining, Software validation, Simulation, Writing- Original Draft.

Sunil Shinde: Project administration, Resources, Writing – Review and editing

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