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Numerical Simulation of 65^0 Delta Wing and $65^0/40^0$ Double Delta Wing to Study the Behaviour of Primary Vortices on Aerodynamic Characteristics

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***Abstract*— In this study, numerical investigation is being carried out to obtain lift, drag, coefficient of lift and coefficient of drag data for 65^0 delta and $65^0/40^0$ double-delta wing at various angles of attack. Aerodynamic study of the 65^0 delta and $65^0/40^0$ wing is carried out by generating unstructured grid mesh with the same boundary conditions, and model was validated to simulate the external flow around the delta and double delta wing at subsonic conditions. The computational results obtained are then compared with the experimental results obtained from literature, the CFD results shows good agreement with the experimental values and thus validates the simulation conducted.The SST turbulence model is used to model the turbulence on external flow at subsonic conditions which captures the vortex formation and breakdown at the leading edges and flow separation on the surface of delta and double delta wing. These results are then used in re-designing of the delta and double delta wing for enhancing the aerodynamic performances. ICEM-CFD is used for generating the unstructured grids and CFX is used as solver to simulate the aerodynamics of the delta and double delta wing.**

Computational analysis is further carried on the 65^0 Delta and $65^0/45^0$ Double Delta wing to improve the aerodynamic performances. A design change is made on the delta and double delta wing by introducing fillet surfaces at the bottom edges and C-shaped structures at the leading edges of the wings. The new design is analysed at different angles of attack from 0^0 to 40^0 with the same boundary conditions as used in validating the CFD results. The results of new design change analysis on delta and double delta wing shows that there is a decrease in drag at all angles of attack by incorporating the new design. This reduction in drag enhances the aerodynamic performance of lift to drag ratio and thus improves overall performance of the delta and double delta wing.

Keywords—Computational Fluid Dynamics (CFD), Integrated Computer Engineering and Manufacturing (ICEM), Shear-Stress Transport (SST)

Nomenclature

C_D	Drag coefficient
C_L	Lift coefficient
D	Drag
L	Lift
AOA	Angle of attack

I. INTRODUCTION

In this technological era right from the nineteenth century defence system is growing rapidly of all nations and reached peek of its technology rather with the compromise of little aerodynamic performance parameters which could have lowered much required defence performance parameters. With the slight increase in the aerodynamic performance of the defence aircrafts keeping all the defence required parameters all together could bring much bigger improvement in the economic operation of the defence aircrafts. In fighter aircraft noise pointing and velocity vector turning are two types of maneuver which require the aircraft to fly at higher angles of attack. As the aircraft requires flying at such high AOA, the study of flow field is important to determine the flight dynamics.

Most of defence aircrafts requires speedy operations rather compromising on fuel consumption and these aircrafts also requires accurate maneuverability no matter with the increase of profile drag. These defence aircraft characteristics bring down the economic aerodynamic operation. Here we focus to increase the economic aerodynamic operation of the defence aircraft system without compromising with the defence characteristics and by varying different aerodynamic parameters and hence it will improve the economic aerodynamic performance. A slight increase in the aerodynamic performance could reduce the fuel consumption and operates the aircrafts economically, thus improving the aerodynamic performance has become the big challenge to the defence aircrafts in this modern technological era.

Delta wings have been evolved to meet the high maneuverable and superior performance requirements. Delta wing has a planform which is triangular in shape and is similar to Greek upper case letter delta (Δ). Thus it is named delta wing [1]. The highly swept leading edged delta wings are employed in high speed fighter aircraft to enhance the aerodynamic performance at high angles of attack. The lift producing mechanism of a delta wing is different from that of a conventional wing. In a conventional wing tip vortices are formed due to pressure differences on the upper and lower surfaces of the wing. As the angle of attack increases the lift increases till the stall angle is reached. As the stall angle is reached the reduction in leading edge suction peak causes lift to drop. The stall angle for a 2D airfoil is 10^0-15^0. In a delta wing as the angles of attack increases, the vortices created due to the pressure difference create a suction effect in the leading edge and the flow remains attached to the upper surface of the wing. This results in the delaying of stall point and supporting high angles of attack. Also the planform of the wing is such that the leading edge of the wing is beyond the vicinity of the shock waves formed at the nose of the aircraft.

The pioneer in delta wing design was **Alexander Lippisch** [1] in Germany in 1931. He studies the ramjet powered delta wing aircraft during the Second World War. The drawback of his research was that the wings he used had thick airfoil proving it unsuitable for transonic flight. **Ahmed Z Garni et al** [2] **,** studied an experimental and numerical investigation to obtain the lift, drag, side force, pitching moment, yawing and rolling moment data at various pitch and side slip angles for a 65^0 delta and $65^0/40^0$ double delta wing. The lift co-efficient, profile drag and drag co-efficient were calculated for both 65^0 delta and $65^0/40^0$ double delta wing at various pitch and sideslip angles. **P.B Earnshaw and J.A Lawford** [3] , have conducted experiment on delta wings in a low speed wind tunnel to investigate separated flow on delta wings of various sweep back angles. He showed that the high swept back delta wings have better aerodynamic characteristics as the flow variations are smooth over them.

In this work a detailed study is conducted on a 65^0 delta and $65^0/40^0$ double delta wing. The flow is characterized and the lift, coefficient of lift, drag and coefficient of drag are calculated at various angles of attack. The computational results are validated with the experimental results and to enhance the performance of the wing a design change is introduced. The new design is produced by introducing fillets at the bottom edges of the wing surface. At the leading edges C-shaped structures are introduced at the leading edges. The design change results in the reduction in drag and enhances the performance of the wing.

II. COMPUTATIONAL TECHNIQUES

The present work is carried out in the following stages:

- **Geometry Modelling:** Modelling of the wing is done using CATIA.
- **Grid Generation:** Grid generation for the model is done by using ICEM – tool.
- **Flow Simulation:** Simulation of delta and double delta wing with appropriate boundary condition and various parameters are obtained using Ansys CFX solver.
- **Validation study:** Validation of the Experimental and Numerical Investigation on a 65^0 delta and $65^0/40^0$ double delta wings [2].
- *New design modification of Wing:* Computational analysis is conducted on both delta and double delta wings with the introduction of fillets at the bottom edges and C-shaped structures on the leading edges.

III. VALIDATION

Experimental and Numerical Investigation done on a 65^0 delta and $65^0/40^0$ double delta wing is validated [2]. The experimental data is regenerated using the CFD tool to check for the accuracy of the computation. In the present study the computational model is modelled using CATIA software. The analysis is carried over ICEM CFD and the computational model is solved using CFX solver [2]. In the present study the SST model is best suitable as there is a need for calculating the flow variations both on the surface and around the wing. The analysis is done at various angles of attack varying from 0^0-40^0 angle of attack. The results are validated with the experimental values obtained from the validation paper [2].

A.Model Description and boundsry conditions:

Delta wing of 65^0 and Double Delta Wing of $65^0/40^0$ with the following specifications are considered for the validation analysis. The flow is analysed around the wing at a velocity of 13 m/s [2]. The model is meshed with unstructured mesh along with prism mesh at the boundaries. The flow near the walls should be given more importance because the main surface flow variations take place at the boundary and walls [2]. The symmetry plane is used on which the wing is attached. The temperature is maintained at 300^0K and pressure is maintained at 1 atm.

Table 1: Shows specifications for a delta wing
[Courtesy: Ahmed Z. Al-Garni et. al.[2]]

Sl. no.	Description	Quantity.
1.	Root chord	0.3 m
2.	Wing span	0.2798 m
3.	Wing area	0.04197 m^2
4.	Aspect ratio	1.865
5.	Velocity	13 m/s
6.	Temperature	300K
7.	Reynolds number	2.67×10^5
8.	Bevel angle	8.5^0
9.	Thickness	0.01 m

Table 2: Shows specifications for double delta wing
[Courtesy: Ahmed Z. Al-Garni et. al.[2]]

Sl. no.	Description	Quantity.
1.	Root chord	0.301 m
2.	Wing span	0.468 m
3.	Wing area	0.0539 m^2
4.	Aspect ratio	4.064
5.	Velocity	13 m/s
6.	Temperature	300K
7.	Reynolds number	2.67 × 105
8.	Bevel angle	8.5^0
9.	Thickness	0.01 m

B. Meshing:

In the present work we use ICEM-CFD software for meshing the 3-D wings [2]. The tetrahedral unstructured mesh is used for meshing the model. Prism layered mesh is used around the boundary layers of the wing.

C. Graphs of Validation CFD with Experiment:

1) Delta wing:

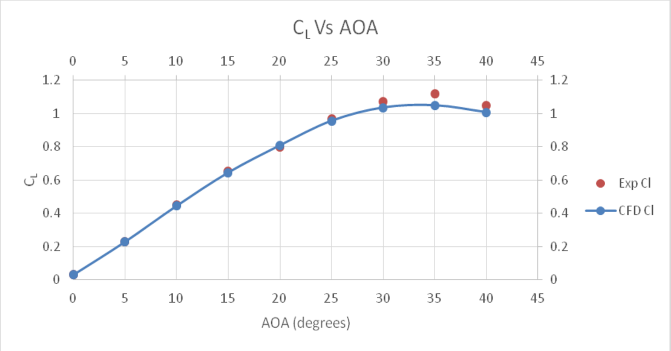


Fig 1 : Shows C_L Vs AOA for Delta wing

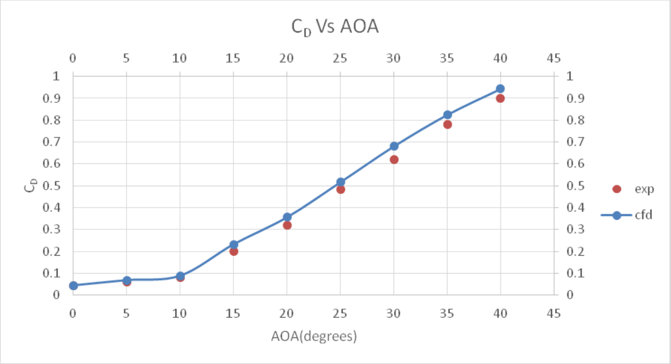


Fig 2: Shows C_D Vs AOA for Delta wing

Figure 1 shows the comparison of CFD with experimental for the co-efficient of lift on the delta wing configuration. We can observe from the graph that the experimental results [2] match the CFD results with an error of ± 0.1% deviation. As the AOA increases the co-efficient of lift also increases upto a certain AOA until stall takes place. Here from the graph we observe that the co-efficient of lift is reducing after 35^0 AOA. The highest co-efficient of lift is 1.1 which is seen at 35^0 AOA.

Figure 2 shows the comparison of CFD with experimental for the co-efficient of lift on the double delta wing configuration. We can observe from the graph that the experimental results [2] match the CFD results with an error of ± 0.2% deviation. The values are in good agreement till 0.1 C_D after which slight deviation is seen.

2) Double Delta wing:

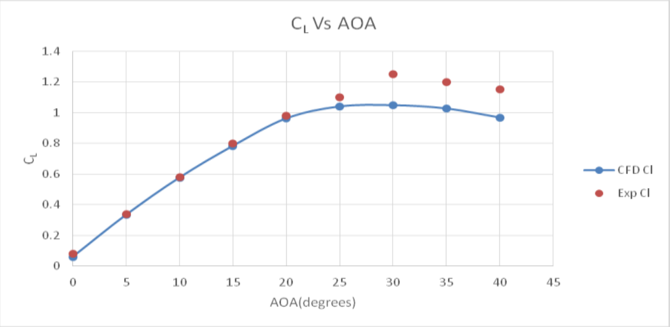


Fig 3: Shows C_L Vs AOA for double delta wing

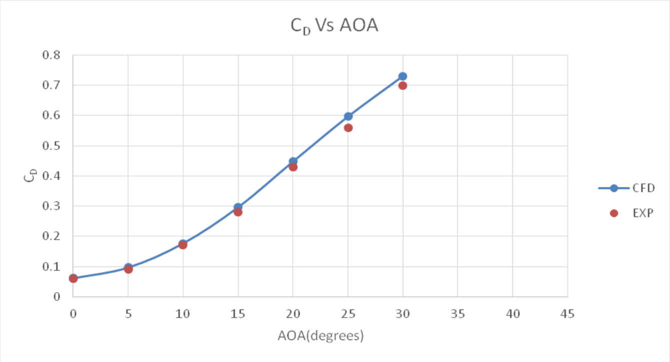


Fig 4: Shows C_D Vs AOA for double delta wing

Figure 3 shows the comparison of CFD with experimental for the co-efficient of lift on the double delta wing configuration. We can observe from the graph that the experimental results [2] match the CFD results with an error of ± 0.2% deviation. When we compare the C_L Vs AOA graphs for delta and double delta wing we observe that at 10^0 and 20^0 AOA, double delta wing gives better co-efficient of lift than delta wing. But at higher angles AOA of 30^0 and 35^0delta wing gives better co-efficient of lift.

Figure 4 shows the comparison of CFD with experimental for the co-efficient of drag on the double delta wing configuration. We can observe from the graph that the experimental results [2] match the CFD results with an error of ± 0.2% deviation. The values are in good agreement till 0.2 C_D after which slight deviation is seen.

IV. RESULTS AND DISCUSSION

The 65^0 delta and $65^0/40^0$ double delta wing which was used for validating the results had sharp edges. For the present study a modification is made on the wing. At the lower edges fillets are introduced to have a smooth flow from the bottom to the top of the wing. Also on the leading edges of the wing C-shaped structures are introduced. The C-shaped structures have small area and these C-shaped structures guide the air smoothly over the upper surface of the wing and thus avoid profile drag.

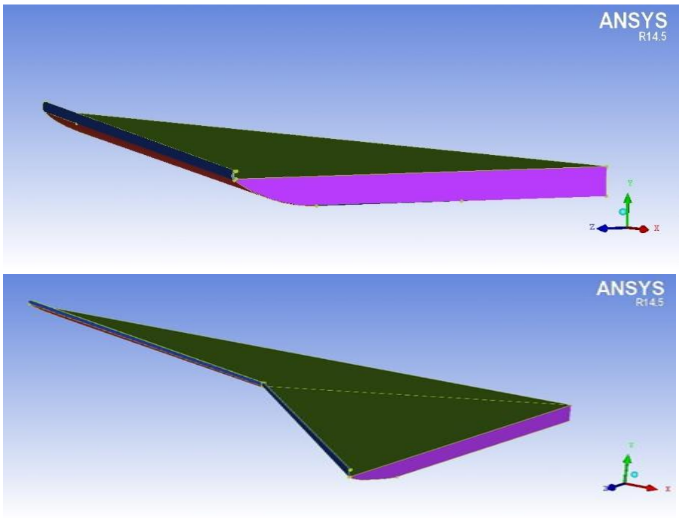


Fig 5 : Shows the Double delta wing with fillets and C-shaped structures

A.Model Description and boundsry conditions:

In the present study, the 65^0 delta and $65^0/40^0$ double delta wing are analyzed using the same boundary conditions as mentioned in table 1 and table 2. The only difference is in the area of the wings because of the incorporation of the C-shaped structures. Hence the area of the delta wing used in the present study is 0.046555 m^2 and area of the double delta wing used in the present study is 0.060052 mm^2.

B.Meshing:

In the present work we use ICEM-CFD software for meshing the 3-D wings. The unstructured prism mesh is used for meshing. The number of elements and nodes are as follows:

Table 3: Shows grid details of wings

Type	Elements	Nodes
Delta wing	2461309	544072
Double delta wing	3074395	672803

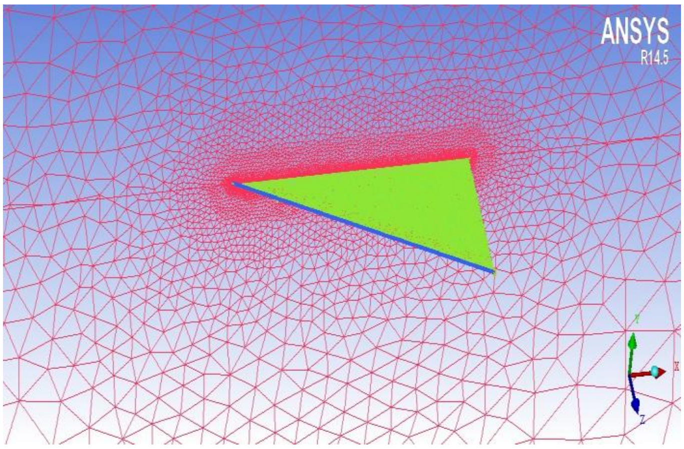


Fig 6 : Shows the view of Unstructured Grid on a Delta wing.

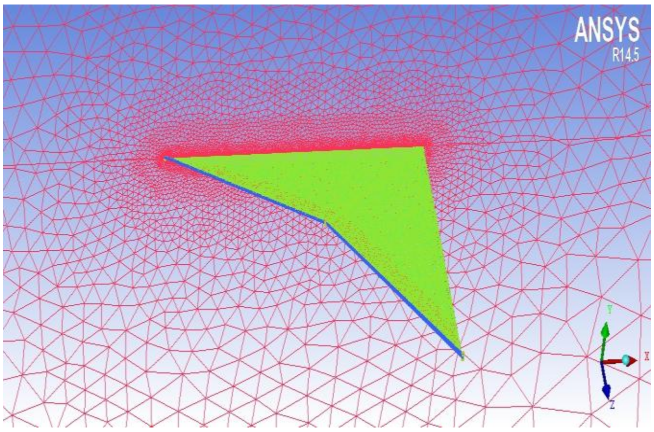
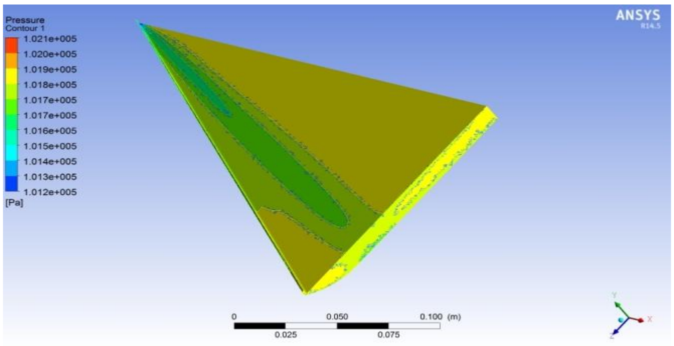


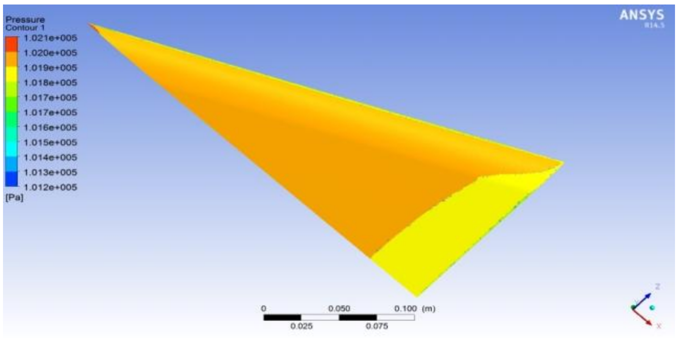
Fig 7 : Shows the view of Unstructured Grid on a Double Delta wing.

C.Pressure Contours and streamlines:

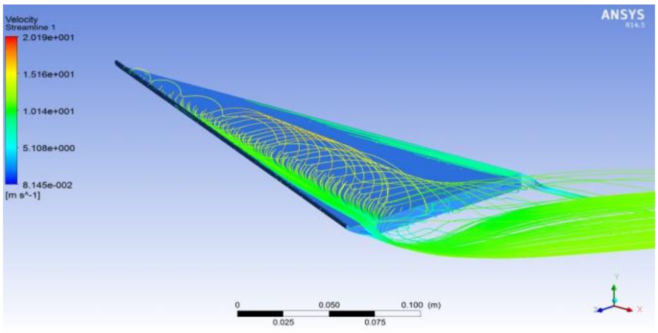
1) Delta wing:



(i) Upper surface

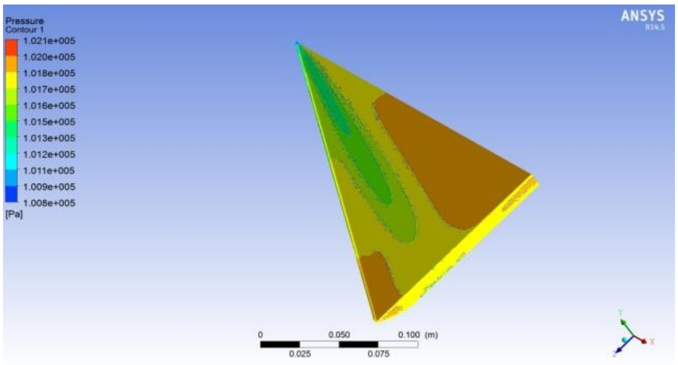


(ii) Lower surface

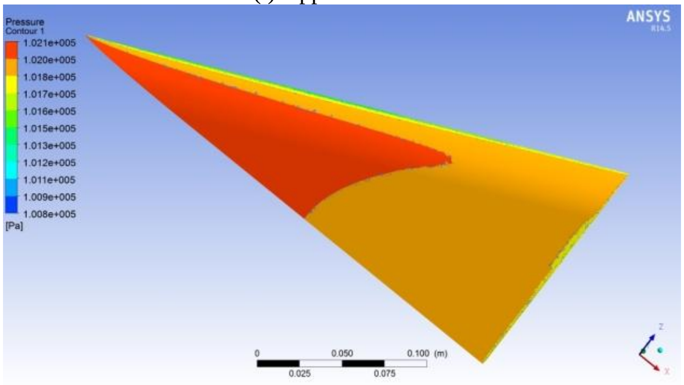


(iii) Streamlines

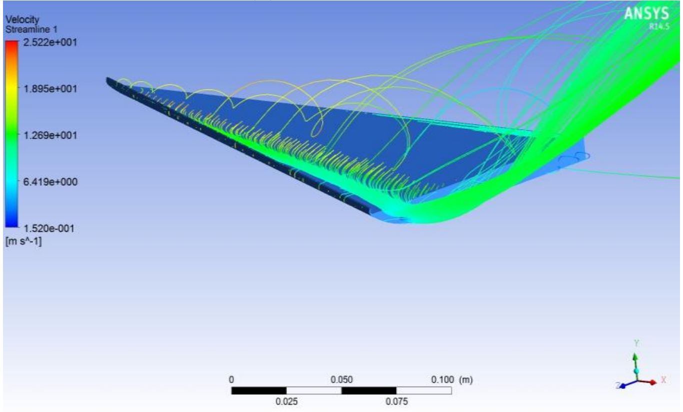
Fig 8 (i-iii): Shows the pressure contours on top and lower surface and velocity streamline on Delta wing at 10^0 AOA.



(i) Upper surface

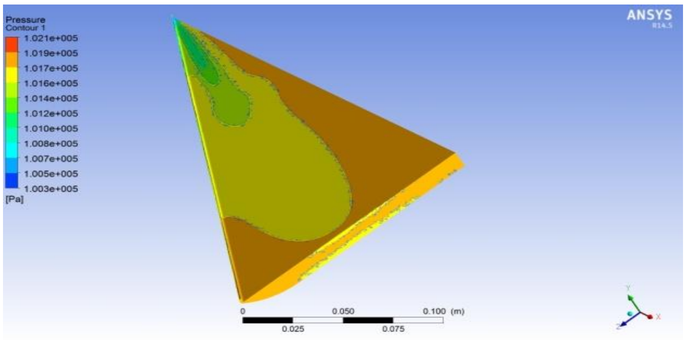


(ii) Lower surface

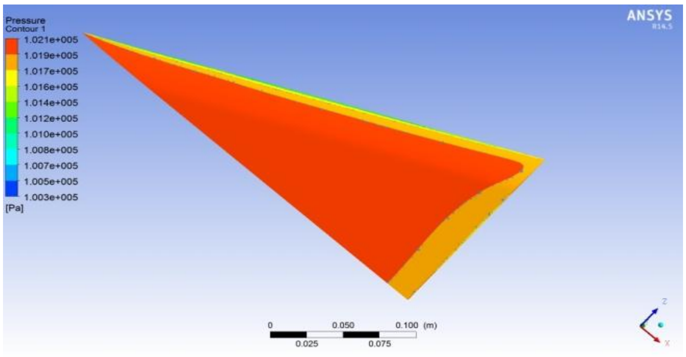


(iii) Streamlines

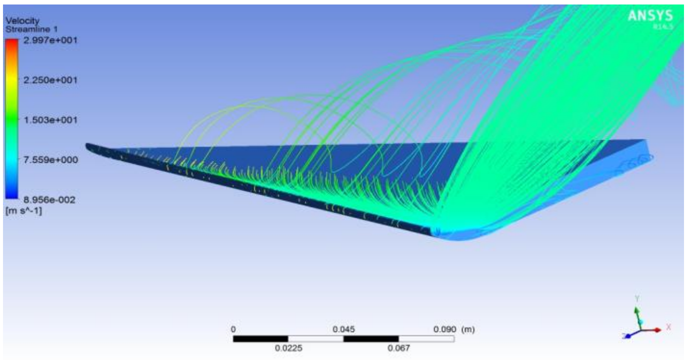
Fig 9 (i-iii): Shows the pressure contours on top and lower surface and velocity streamline on Delta wing at 20^0 AOA.



(i) Upper surface



(ii) Lower surface



(iii) Streamlines

Fig 10 (i-iii): Shows the pressure contours on top and lower surface and velocity streamline on Delta wing at 30^0 AOA

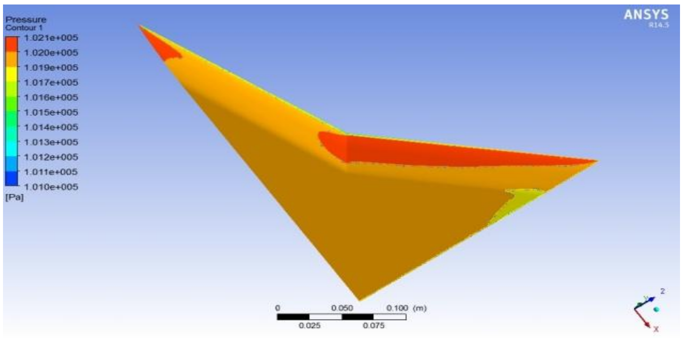
Figures 8, 9 and 10 show the pressure variation and streamlines on the surface of the delta wing at 10^0, 20^0 and 30^0 AOA. The variation of pressure on the top surface is more than that on the lower surface. The flow from the bottom leading edge is easily coming towards the top surface due to the chamfered bottom leading edge nature of the delta wing and this bottom air is mixing with the top surface air at the top leading edge of the delta wing and tends to form the vortex at the top leading edge of the wing.

The flow velocity locally gets energized due to the vortex formation and thus the flow velocity increases and the velocity at the core of the vortex will be higher than the surrounding vortices. These vortices formed will increases the flow velocity locally on the top surface of the delta wing which in turn causing the pressure to drop on the top surface as compared to the bottom surface of the delta wing, this high pressure on the bottom surface and low pressure on the top surface.

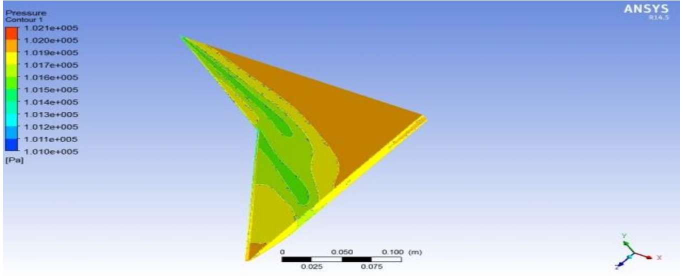
Here on the top surface of the delta wing the vortices which are formed on the top leading edge of the wing is also making the flow more turbulent. The pressure gradient on the top surface is much higher as the flow passes from tip to the trailing edge and thus the flow separation is also occurring on the top surface which increases drag.

This pressure gradient on the top and bottom surface of the delta wing produces the lift to the delta wing and in addition the vortices formed on the top leading edge of the wing enhance lift generation [6] along with the increase of drag.

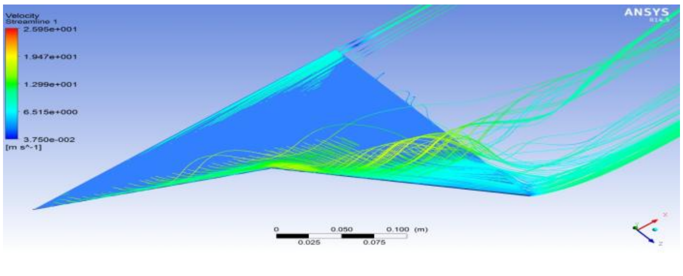
2) Double Delta wing:



(i) Upper surface

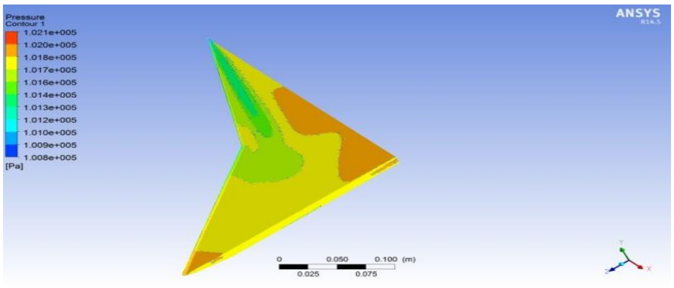


(ii) Lower surface

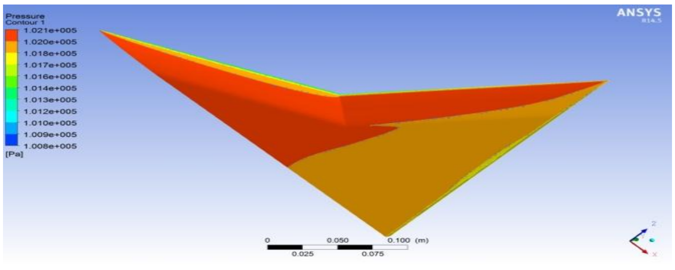


(iii) Streamlines

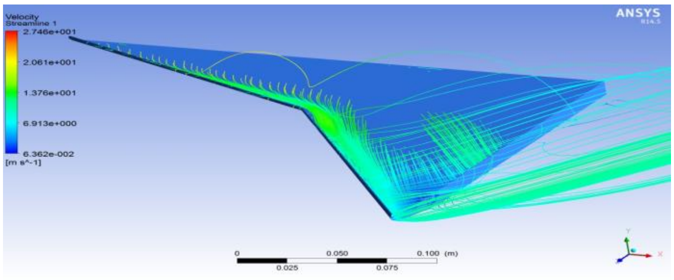
Fig 11 (i-iii): Shows the pressure contours on top and lower surface and velocity streamline on double delta wing at 10^0 AOA



(i) Upper surface

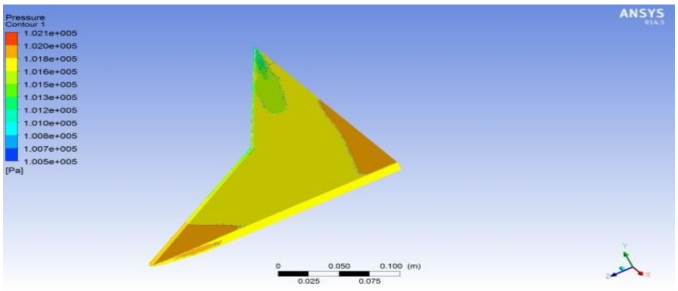


(ii) Lower surface

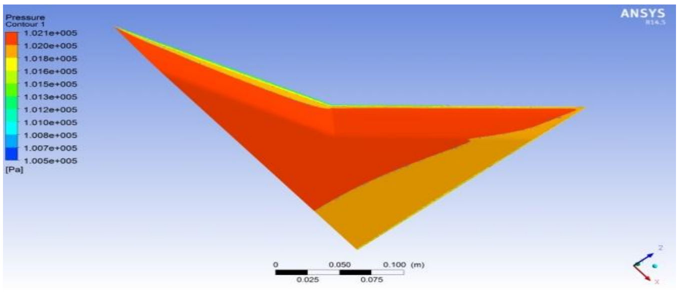


(iii) Streamlines

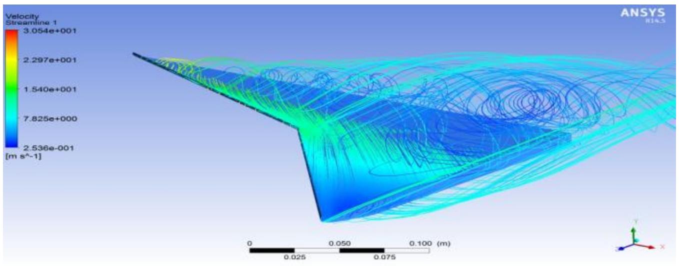
Fig 12 (i-iii):: Shows the pressure contours on top and lower surface and velocity streamline on double delta wing at 20^0 AOA



(i) Upper surface



(ii) Lower surface



(iii) Streamlines

Fig 13(i-iii): Shows the pressure contours on top and lower surface and velocity streamline on double delta wing at 30^0 AOA

Figure 11, 12 and 13 show the pressure variation and streamlines on the surface of the delta wing at 10^0, 20^0 and 30^0 AOA. The C-shaped structures allow the formation of very few vortices on the wing surface and hence the extra lift component due to the vortices does not contribute to the lift generation. Therefore the vortices formed here are less which also result in reduced turbulence. The C-shaped structures guide the flow smoothly over the surface.

The pressure variation on the lower surface is always less than the pressure variation on the top surface. This is due the change in design from sharp edge to fillet edged bottom leading edge of delta wing.

The velocity streamlines indicate the velocity variation on the surface of the wing. The flow over the top surface may turbulent and flow separation also takes place. Here on the top surface of the delta wing the vortices which formed on the top leading edge of the wing is less. Thus the turbulence formed is also less and thus the pressure gradient also decreases which results in reduction in flow separation and hence drag is also reduced.

A. *Graphs of Validation CFD with Design change CFD results:*

1) Delta wing:

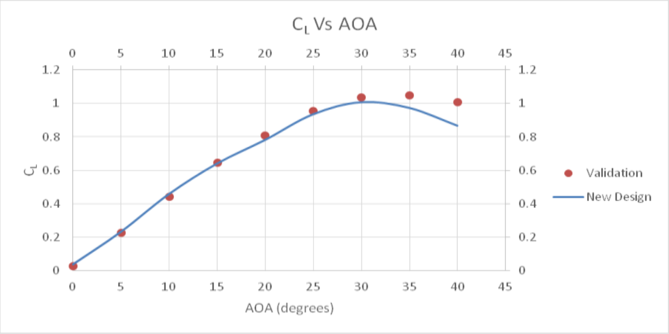


Fig 14: Shows C_L Vs AOA for delta wing

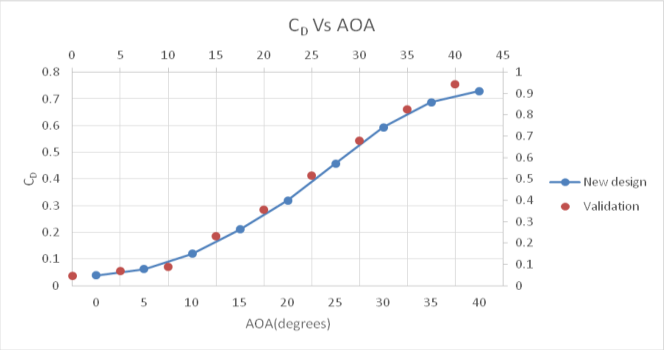


Fig 15: Shows C_D Vs AOA for delta wing

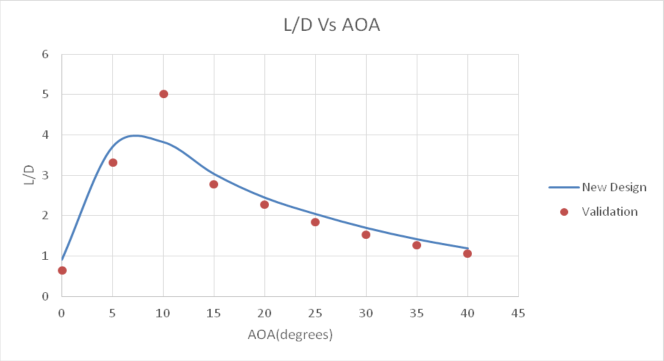


Fig 16: Shows L/D Vs AOA for delta wing

The SST turbulence model has been considered for CFD analysis with the same boundary conditions used for validation.

From figure 14 we observe that till 30^0 AOA the co-efficient of lift is increasing, after which the curve is decreasing which indicates the decrease in lift after 30^0 AOA. The outcome shows validation gives better co-efficient of lift than the design change. When a C-shaped structure is introduced on a wing the vortices formed on the upper surface of the wing are few. Hence the pressure variation is low on the top surface of the wing. This reduces the difference in pressure between the upper and lower surface of the wing which results in the reduction in lift. The C-shaped structures guide the flow smoothly over the wing which results in reduction of drag. This is due to the less vortex formation and smooth variation of flow.

Figure 15 shows the graph of L/D Vs AOA. This graph is plotted to show the performance of the wing. The lift by drag ratio is a very important parameter to obtain the performance of the wing. If the lift is more than the drag then the aircraft moves forward. But of the drag is more than the lift then the aircraft is pulled backward. Hence a plot of lift by drag Vs angle of attack shows the actual performance. We can observe that the new design is showing a better performance than the validation. But at 10^0 angle of attack the validation wing is showing better performance. But for all other angles off attack we can see that the new design incorporating C-shaped structures and fillets gives better performance.

2) Double Delta wing:

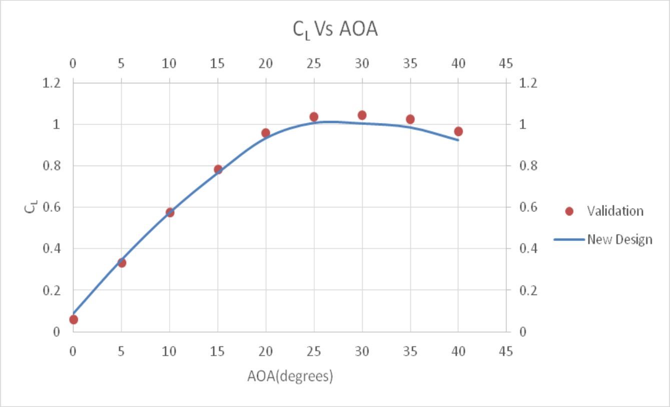


Fig 16: Shows C_L Vs AOA for delta wing

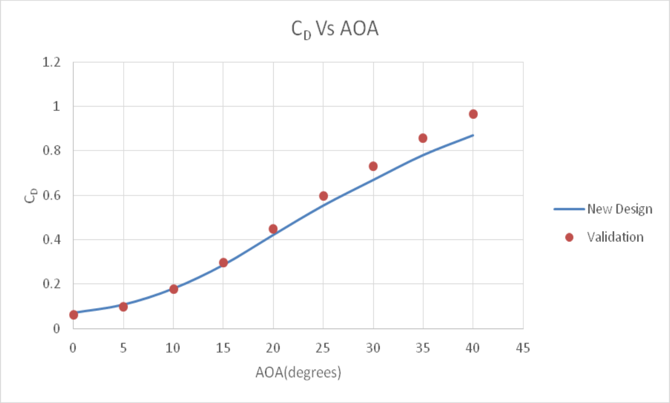


Fig 17: Shows C_D Vs AOA for delta wing

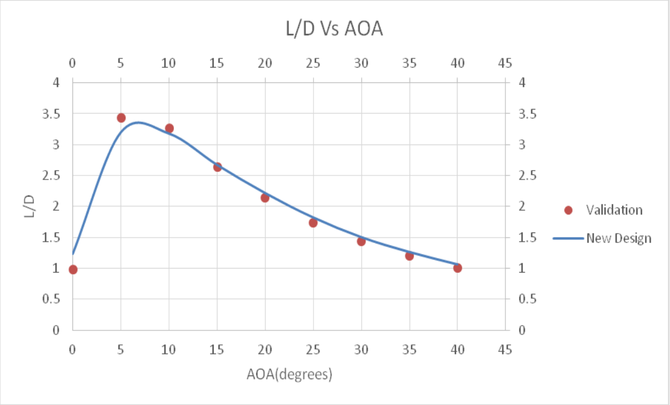


Fig 18: Shows L/D Vs AOA for delta wing

We observe that till 35^0 AOA the co-efficient of lift is increasing which is observed by rise in curve, after which the curve is falling. This means that the lift is decreasing after 35^0 AOA. The highest angle of attack at which the aircraft can fly is 35^0. We also observe that the validation is giving better co-efficient of lift than the design change. This is because when a C-shaped structure is introduced on a wing the vortices formed on the upper surface of the wing are few. Hence the pressure variation is low on the top surface of the wing. This reduces the pressure gradient of the wing which results in the reduction in lift. At lower AOA the lift produced by double delta wing is more than delta wing, but at higher angles of attack the delta wings produce more lift.

We observe from the graph that as the angle of attack is increasing the drag also increases. The present work and validation results are plotted for different angles of attack. We can observe that the drag obtained by the new design is lower than that of the validation. At lower angles of attack the validation design proves to be better. But at higher angles of attack we have observed that the introduction of C-shaped structures have resulted in the reduction of drag. This is due to the less vortex formation and smooth variation of flow. The variation of pressure is also less and the smooth flow over the surface delays the stall point.

Figure 18 shows that performance of the $65^0/40^0$ double delta wing. Better the lift by drag ratio, better the performance and fuel consumption. In the present study lift by drag ratio for the design change is better than for the validation. The design change reduces the drag which in turn enhances the lift by drag ratio.

V. CONCLUSION

The numerical investigation is carried out on a 65^0 delta and $65^0/40^0$ double delta wing. The analysis is carried out at different angles of attack ranging from 0^0-40^0. SST turbulence model is used for the analysis because in the present study we are dealing with the flow on the surface of the wing and also with the flow around the wing. Lift, drag, co-efficient of lift and co-efficient of drag is obtained at different angles of attack and these results are compared with the experimental data of **Ahmed Z Garni et al** [2]. The CFD results show good agreement with the experimental data with an error of 2%. Thus the CFD results are validated.

In the present study, a design change is made by incorporating C-shaped structures on the leading edges and fillets are made on the bottom edges of the wing. Computational analysis is carried on a 65^0 delta and $65^0/40^0$ double delta wing incorporating these changes. The analysis is carried out at different angles of attack from 0^0-40^0 with the same boundary conditions as per validation. By introducing the C-shaped structures on the leading edges, it was observed that the vortices formed due to pressure differences were reduced. The reduced vortices did not contribute much is generating the extra lift component. Instead The C-shaped structures collected the flow on the upper surface and directed it rearward smoothly. This resulted in the smooth flow over the wing and reduction in pressure variation and hence decrease in drag was observed.

The study proves that by introducing the C-shaped structures the drag has reduced. The performance can be shown by plotting a graph lift/drag Vs angle of attack. It shows that the wings incorporating the design change shows better performance that the wings used for validation. Increase in performance in turn reduces the fuel consumption and the aircraft can be used to maneuver at higher angles of attack.

1. By introducing the C-curved structure at the leading edge of the delta/double delta wing. The vortices formed are lesser than the actual (validation) delta/double delta wing.
2. This is because the C-curved structure is not allowing the top surface flow to mix at the leading edge with the flow coming from bottom, thus reducing the vortex formation at leading edge.
3. There is no additional lift generating on the new-design delta/double delta wing due to reduction in leading edge vortices, which both (vortices and additional lift) was higher in the actual (validation) delta/double delta wing. Thus drag associated with the vortices is also reduced in the new-design delta/double delta wing.
4. The presence of C-curved structure at the leading edge is reducing the vortices formed due to flow separation. Thus it shows, the flow separation is also reducing.
5. Therefore drag due to flow separation on top surface of new design delta/double delta wing is reduced.
6. The overall performance of Lift to drag ratio of the new design delta and double delta wing is improved than the actual (validation) delta/double delta wing

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