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CFD investigation of pitch-up in a Transonic regime

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ABSTRACT

Double delta wing aircraft experiences a pitch up at high angle of attack in transonic regime. This is primarily due to vortex breakdown, which leads to pronounced pitch-up and affect aircraft stability and control, limit the aircraft usable AOA_{max} and, therefore, load factor and maneuverability. It is therefore important to understand the vortex break down, flow separation and shock interactions. With the introduction of strakes and their positions will enhance the aerodynamic characteristic of the wing at high angle of attack..

CFD simulations are performed using commercially available software CFD++ to investigate the sudden pitch-up in Transonic Regime. Studies have also been carried out for selecting a suitable strake and its position for reducing pitch up severity. Based on the results, Strake geometry at position3 has shown significant improvement in eradicating the pitch up and also reducing the severity at high AOA.

Key Words: CFD, Transonic, Delta wing, Shock, Pitch up, Vortex break down

1. INTRODUCTION

Low aspect ratio wings with highly swept leading edges are the common choice for supersonic cruise aircrafts because of their low drag benefits in supersonic flight. However, these planforms generally have poor subsonic speed aerodynamic characteristics such as low lift-to-drag ratios and low lift curve slopes, $CL\alpha$. To compensate for the deficiencies of these wings, double delta planforms have been employed (i.e., $\Lambda 1 < \Lambda 2$). This improves subsonic lift-to-drag ratio, and increases the $CL\alpha$. However, these wings are subjected to pitch-up at high angle of attack at transonic regime which can restrict usable AOAmax. Pitch-up is a result of non-linear aerodynamic effects like leading edge vortex flow, outer wing stall, and vortex breakdown. These effects are difficult to model with linear aerodynamic methods and continue to pose a challenge for CFD.

With the introduction of strakes and their positions will enhance the aerodynamic characteristic of the wing at high angle of attack. The highly' swept strake is an additional lifting surface which enhances a stable vortex formation. This strake vortex persists over the wing and induces a strong outflow, which energizes the boundary layer on the upper surface of the wing and keeps the flow vortex attached to a higher angle of attack than in the case of a wing without a strake. Therefore, strake increase the lift to drag ratio of delta wings at higher angle of attack[1]. Strake with double delta wing energizes the main wing vortex that increases in size and strength with distance downstream of the wing. Strake and wing vortices have the same direction of rotation and at high angles of attack their trajectories entwine due to interaction. A limit to these effects is reached once the angle of attack attains values where vortex breakdown occurs over the wing.

In this paper, work has been carried to investigate transonic pitch-up using commercially available software CFD++ on two different configurations (i.e.) first design of double delta wing configuration (delta1), later the second configuration evolved by enlarging the first design in span-wise and lengthened along axial direction to meet the requirements (delta2).

2.GEOMETRY DETAILS

Double delta wing configuration is analysed for the transonic pitch up investigation as shown in Figure 1. Considered half geometry for transonic longitudinal simulation, assuming the flow is symmetry and also for reduced computational time. Two strake shapes, Strake1 and Strake2 shapes on double delta wing configuration are shown in Figures 2 & 3 and Figure 4 shows Strake 2 at different positions. Strake 1 acts more like a fixed Canard, while Strake 2 is based on study of existing literature. Strake 2 LE sweep is the same as that of the double delta wing sweep ($\Lambda 1$) as suggested in [1] for enhancing the vortex strength and keeping the flow attached up to high AOA. The three positions of Strake 2 are derived from [2] which discusses importance of locating the strake to achieve aerodynamic improvements at high AOA.

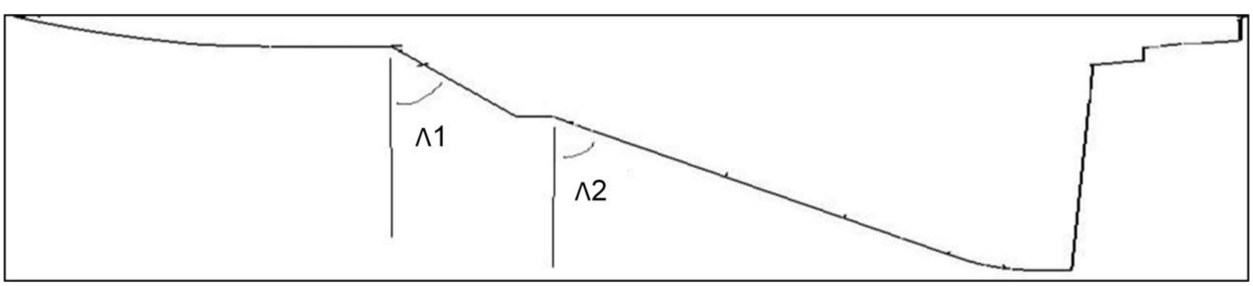

Fig.1: Double delta wing aircraft

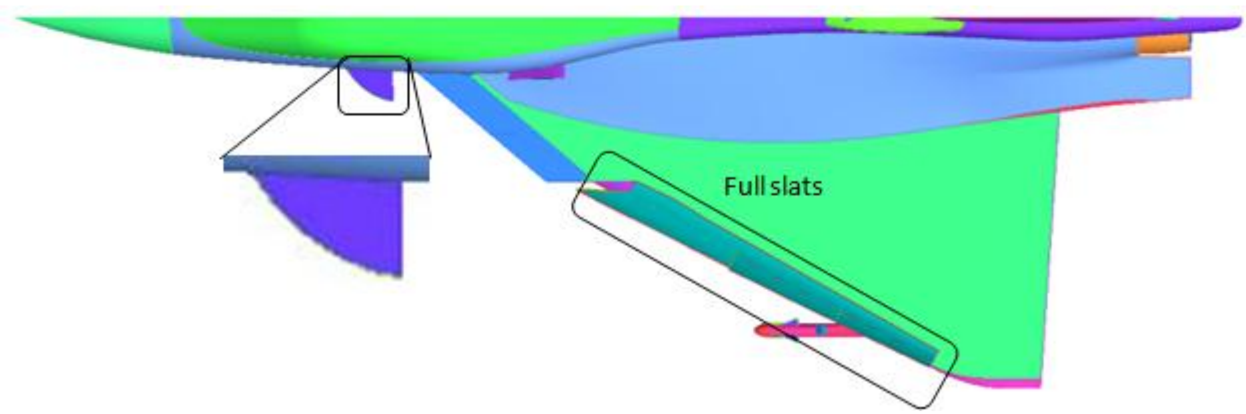

Fig.2: Double delta wing aircraft with Strake 1

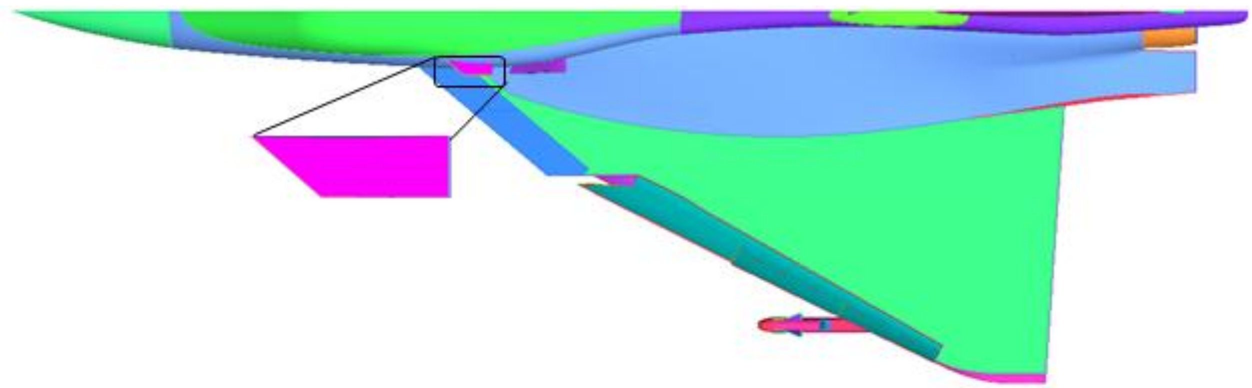
Fig.3: Double delta wing aircraft with Strake 2

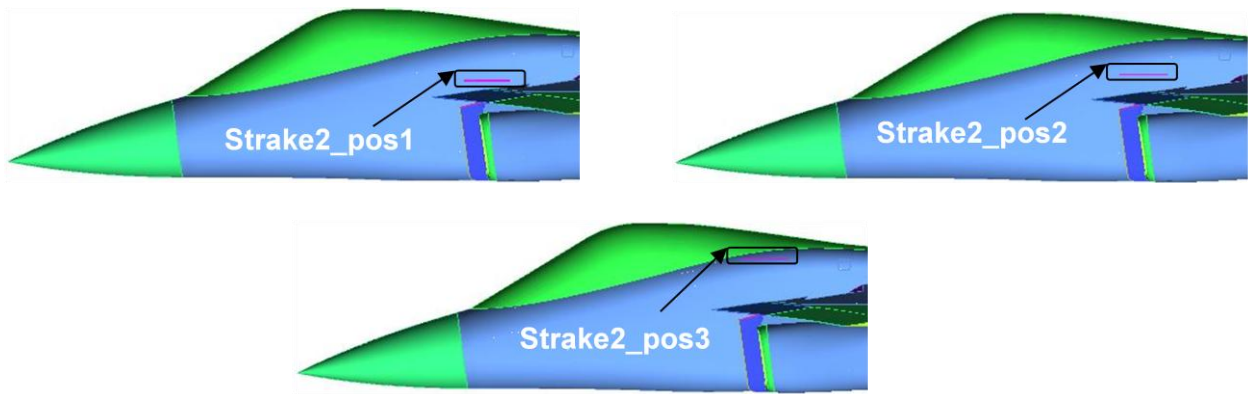

Fig.4: Double delta wing aircraft with Strake 2 at different positions

3.MESH

Meshing is accomplished in ICEM CFD, Version 14.0-1. ICEM CFD is a Ansys tool used for modelling and meshing geometries. The reason for this tool selection is because it is simple and powerful, unstructured grid generation algorithm with good quality. For an accurate prediction of vortex break down and flow separation, adequate grid density at volume was adopted based on previous experience on high speed, high AOA flow simulations to capture pitch-up phenomenon as shown in Figure 5. Surface mesh (triangular elements) is shown in Figure 6. Unstructured volume mesh is generated using Delaunay method as shown in Figure 7.1, which has tetrahedron grid elements. Quadratic elements were generated in the prism layer to capture the growth of boundary layer near the wall as shown in Figure 7.2. Mesh details is shown below Table 1

Mesh details	
Mesh Method	Delaunay
Total Number Mesh elements ($x10^6$)	44
Total Number of Surface cells ($x10^6$)	1
Reynolds Number ($x10^6$)	Flight conditions
1st Layer Height, mm	0.0018
Prism Layers Growth rate	1.25
Total height of Prism layers, mm	35

Table.1 : Mesh details for double delta wing aircraft.

Surface Mesh

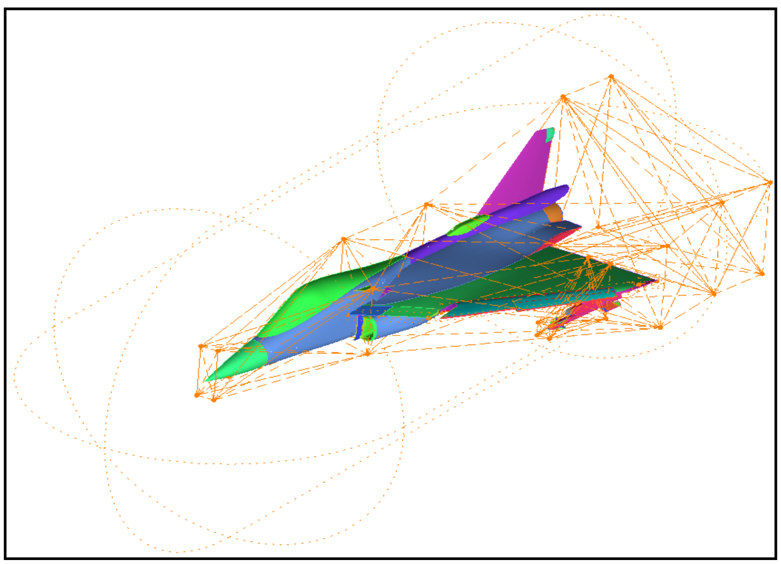

Fig.5: Density boxes over double delta wing aircraft.

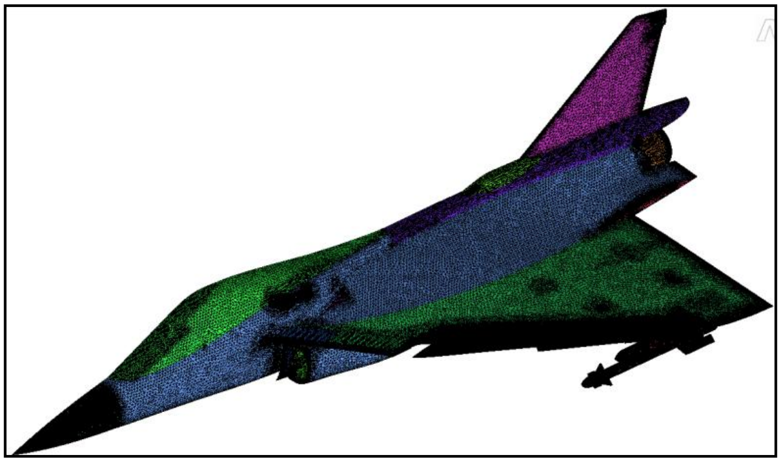

Fig.6: Surface tetra mesh over double delta wing aircraft.

Volume Mesh

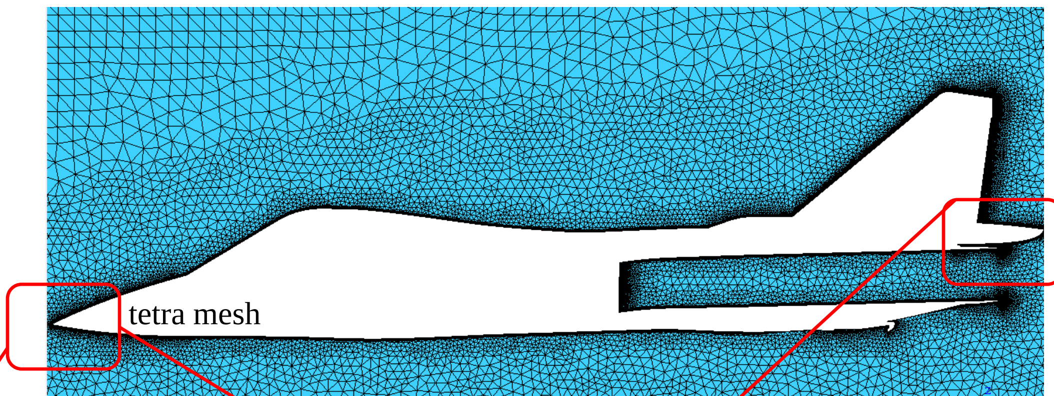

Fig.7.1: Volume mesh over double delta wing aircraft.

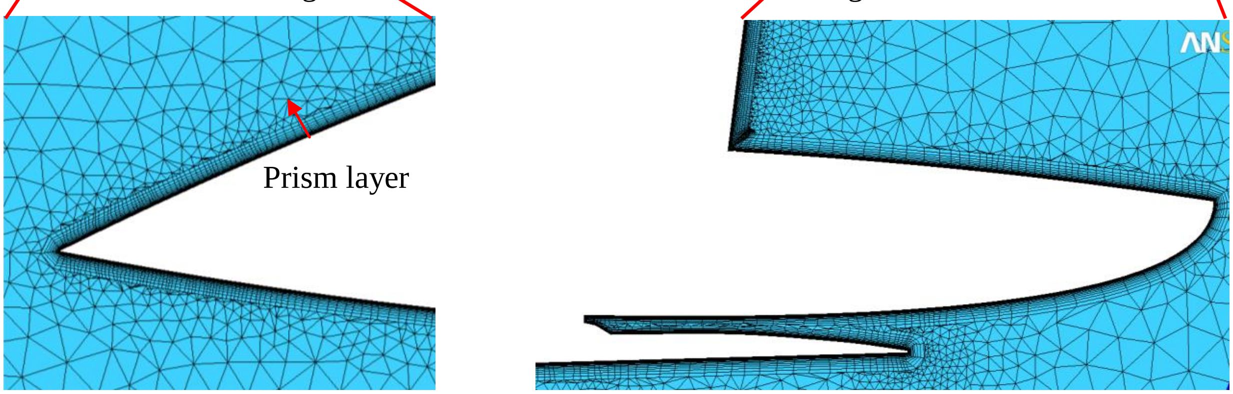

Fig.7.2: Prism Layers on the Volume Mesh.

4.NUMERICAL METHOD

For CFD analysis, considered three dimensional ellipsoidal domain which was approximately 24 times of fuselage length along major axis and 15 times of fuselage length on minor axis. The far field set as inlet boundary conditions. No slip wall boundary conditions are imposed for double delta wing aircraft. Below Table.2, provides boundary condition details for double delta wing aircraft.

Solver details	
Solver	CFD++
Mach number	0.8
Turbulence model	SST
Altitude (KM)	1.5km
Total no Iterations	2000
Global Residual set	$1e^{-8}$
AOA	Sweep
Turbulence viscosity value (fmu)	10

Table.2: Boundary condition details for double delta wing aircraft.

5.RESULTS

5.1 Aerodynamic Pitch up:

Pitch-up is identified by abrupt change in slope of the CM(α) and CM(CL) by plotting dCM/dCL(α) and dCM/dα curves. It is quantified by the highest value of these derivatives within the AOA range of interest.

5.2 CFD Validation:

Wind tunnel data available for delta1. Figures 8(a) and (b) show comparison of CFD with wind tunnel data for delta1. While the overall trends of CFD results are similar to wind tunnel data, the slope of CPM plot and the AOA at which maximum CPM occurs are different. CFD captures quite well in the linear separation plays an important role. The maximum magnitude of (dCM/dCL) & (dCM/dα) is predicted by CFD is not noticed in wind tunnel data, CFD also over-predicts CL at high AOAs.

5.3 Delta1 vs Delta2:

Figure 9(a) compares CFD results of CPM and CL between delta1 and delta2. For delta2, CM0 is higher than delta1 due to its larger span. The CL plot for delta2 has a higher slope attributed to the larger span since coefficients for both aircraft are referred to common wing area of delta1. Plots of dCM/dCL and dCM/dα vs AOA are shown in Figure 9 (b). Magnitude of the pitch up for delta2 is higher than delta1. However, delta2 has higher instability, which can potentially restrict the AOAmax to less than the delta1. Therefore, it is important to understand and restrict this vortex break down phenomenon.

5.4 Strake1 on delta2:

CFD runs are performed for limited angle of attacks to check the pitch-up characteristics. Results for Strake1 shown in Figure 10(a) & 10(b) are encouraging as CPM and CL characteristics are improved at high AOA in terms of delayed pitch-up with reduced magnitude. However, Strake1 located on the front fuselage can possibly interfere with air intake flow, particularly with reference to buzz onset boundary at supersonic speeds.

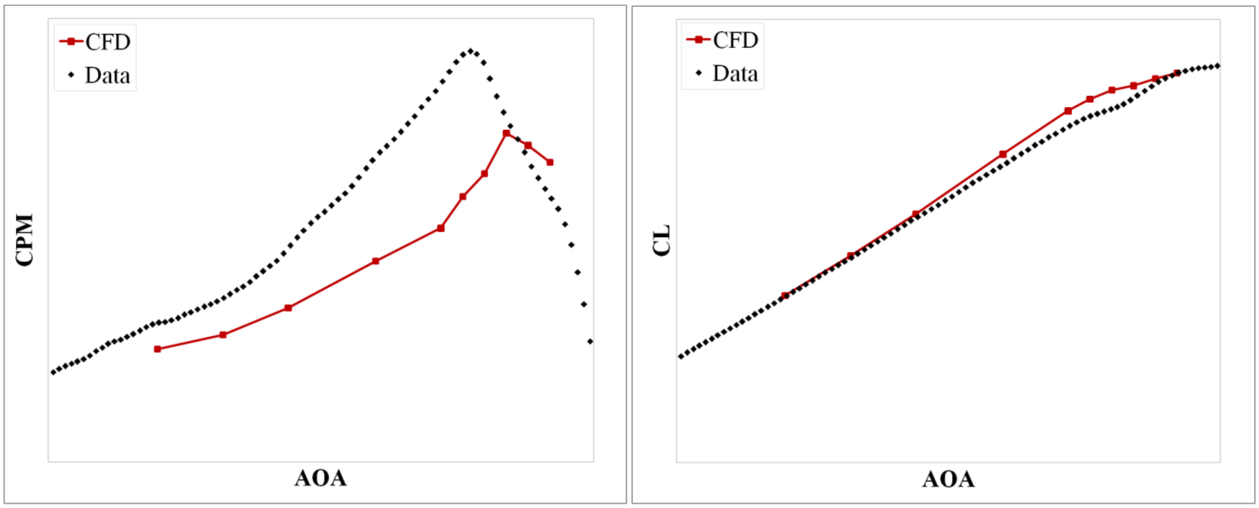

Fig.8 (a) : CPM, CL plots for delta1 .

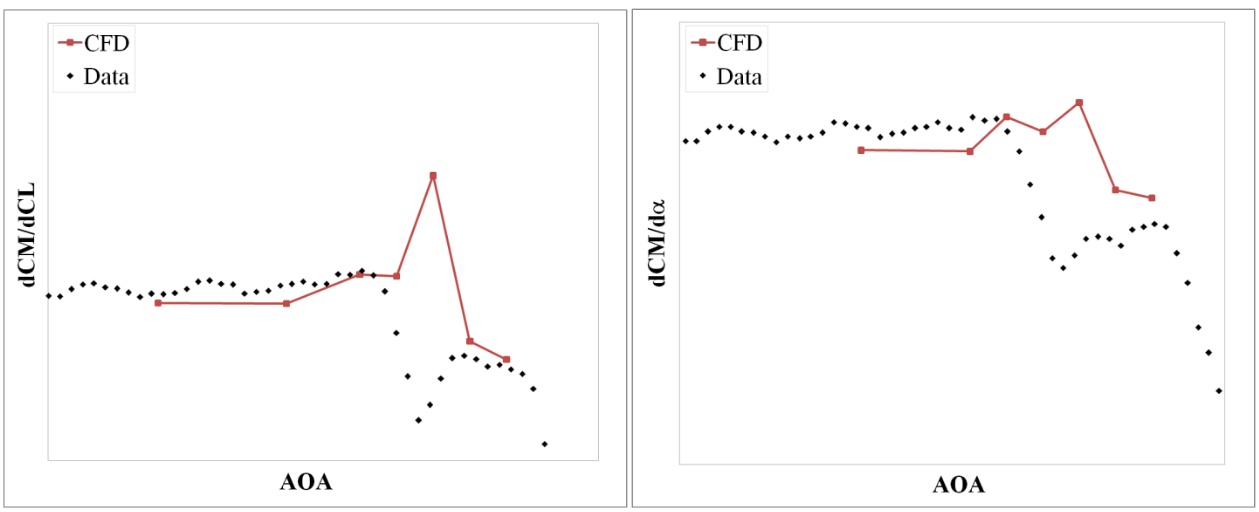

Fig.8(b): dCPM/dCL, dCPM/dα plots for delta1.

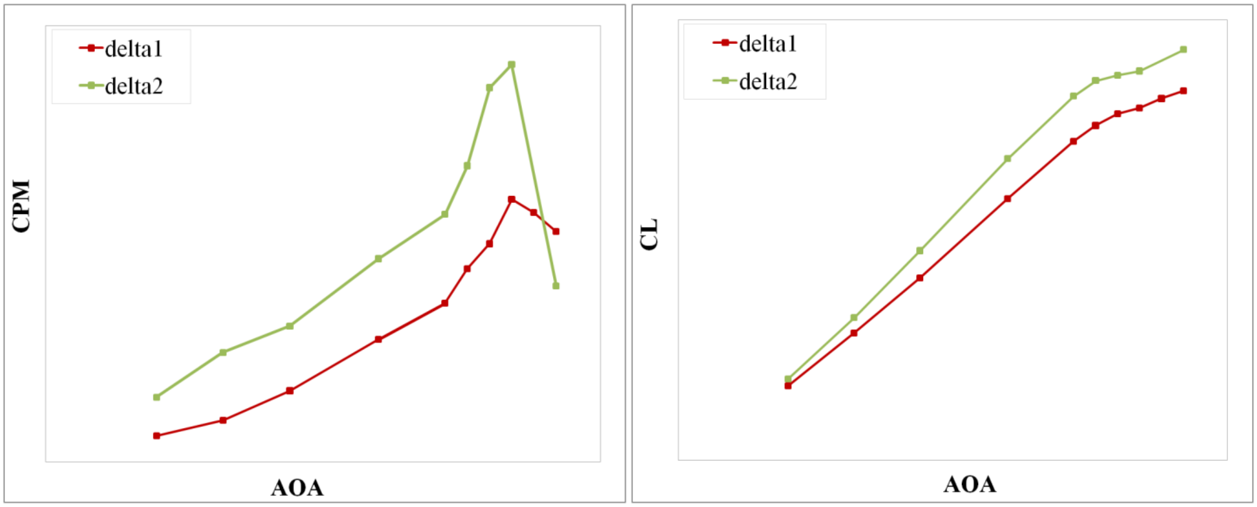

Fig.9 (a): CPM, CL plots between delta1 and delta2.

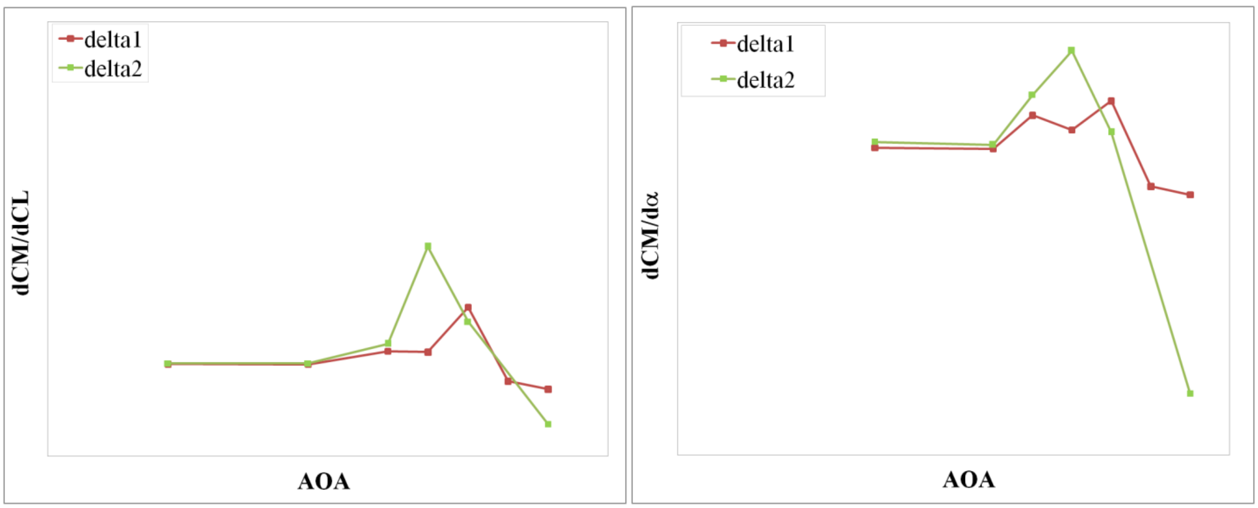

Fig.9 (b): dCPM/dCL, dCPM/dα plots between delta1 and delta2

5.5 Strake2 on delta2:

Strake 2 geometry (Figure 3) has been analyzed at three different positions (Figure 4) and the results are presented in Figures 11(a) &11(b). Relatively, Strake 2(pos 3) has better aerodynamic characteristics than other two positions, i.e., smallest pitch-up magnitude delayed to highest AOA and with highest CLmax.

5.6 Reasons for Transonic Pitch-Up:

Further analysis is carried out to understand the flow behaviour and contributing factors for transonic pitch-up with Strake 2(pos 3) on delta2 (Figures 12 to 22).

a) Shock Strength:

Iso-contours of shock strength at M=0.8, at particular AOA are shown in Figure 12 for delta1, delta2 and delta2 with Strake 2(pos 3). Leading edge vortices create a strong shock standing aft of the double delta in the stub wing region. This deflects the vortices outboard along the double delta leading edge, thereby creating suction ahead of the Moment Reference Point (MRP), while flow separation behind the shock reduces lift in the region behind the MRP, resulting in the pitch-up phenomenon. delta1 is observed to have a multiple shock system, possibly because since its shape was not area ruled effectively. The shock strength is greater for delta2 having a longer wing span as compared to delta1. Presence of Strake 2(pos 3) just upstream of this shock system marginally reduces its strength and helps in controlling pitch-up.

b) Surface Cp Distribution:

Towards understanding the contribution of Strake 2(pos 3), iso-contours of Cp on wing upper surface and their span-wise distribution at three X=constant stations are plotted in Figures 13 to 18. At station forward of MRP, considered three angles near the pitch up and plotted as shown in (Figures 13 & 14), Strake 2(pos 3) distinctly reduces suction in the inboard region of the wing while there is a marginal increase on the outboard wing. Further behind at MRP location, presence of Strake 2(pos 3) increases suction and therefore lift in the inboard region, while the outboard region remains unaffected (Figures 15 & 16). A similar behavior is observed further aft of MRP and the higher lift observed behind the MRP reduces the pitch-up magnitude (Figures 17 & 18).

c) Flow Field Cp Distribution:

Figure 19 shows flow field iso-contours of Cp at X=constant stations and their progress along the length of the fuselage. While delta2 has higher suction near the wing leading edge than delta1, the vortices appear to lose energy towards the aft region of the wing. Adding Strake 2(pos 3) to delta2 energizes the vortices resulting in higher suction levels persisting near the wing trailing edge, similar to those seen on delta1. This justifies reduction in pitch-up magnitude with the introduction of this Strake.

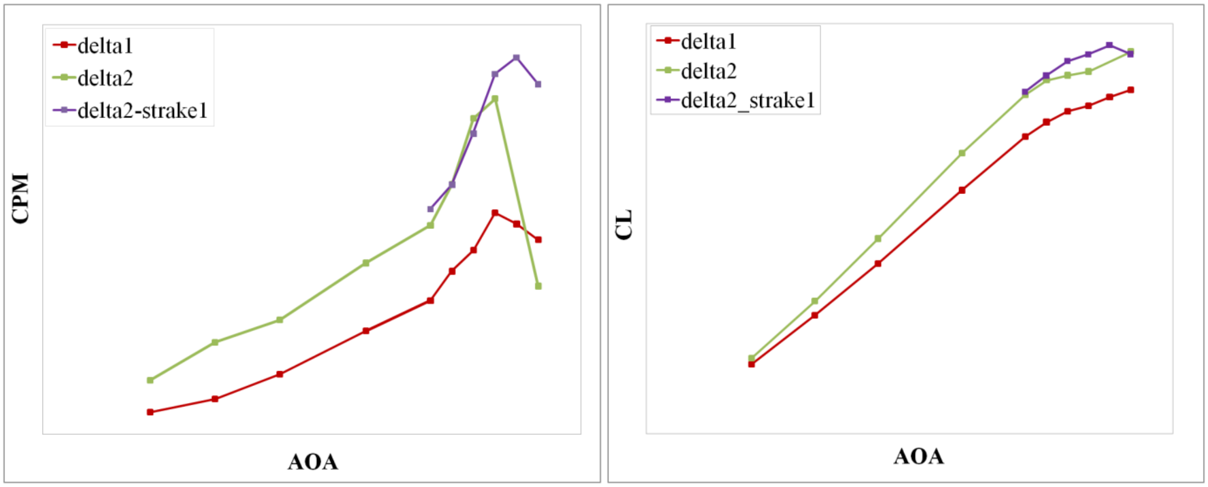

Fig.10 (a): CPM, CL plots for Strake 1 on delta2.

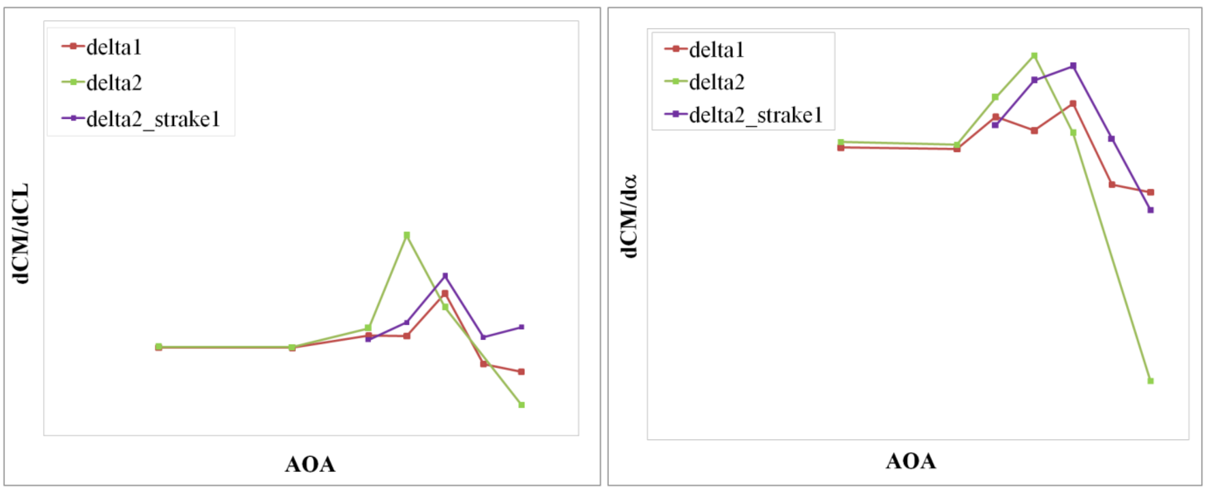

Fig.10 (b): dCPM/dCL, dCPM/dα plots for Strake 1 on delta2.

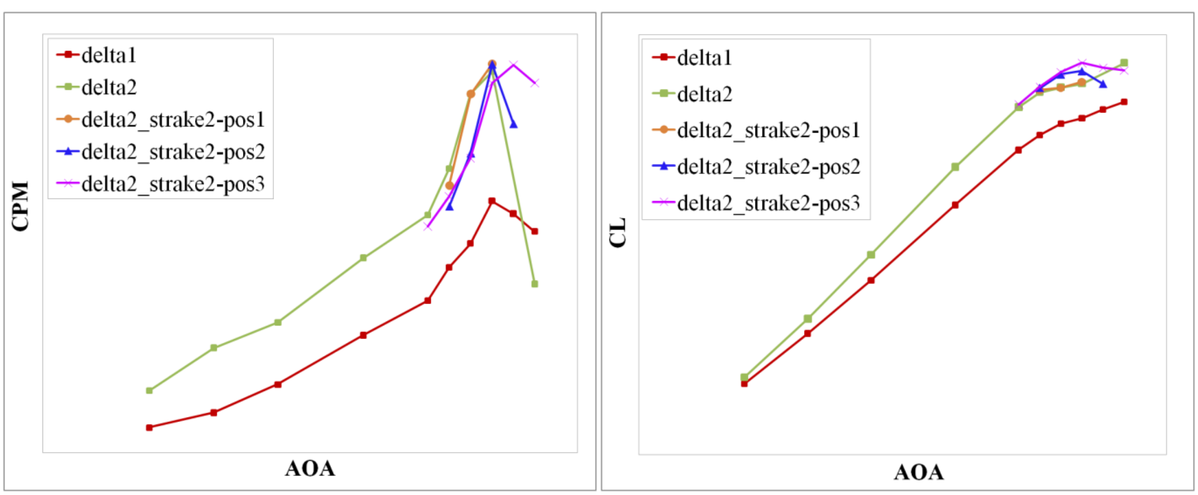

Fig.11 (a): CPM, CL plots for Strake 2 on delta2.

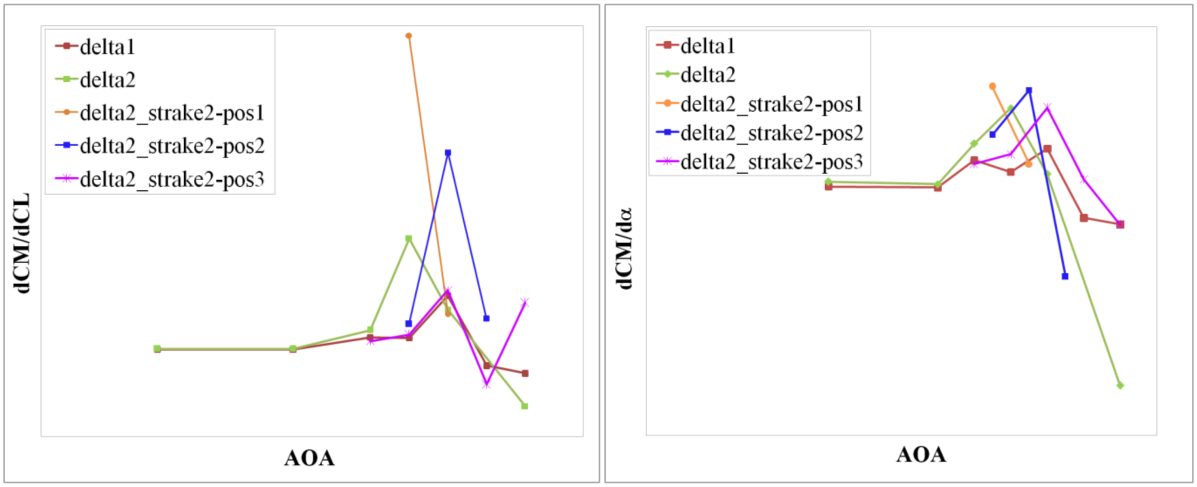

Fig.11(b):dCPM/dCL, dCPM/dα plots for Strake 2 on delta2

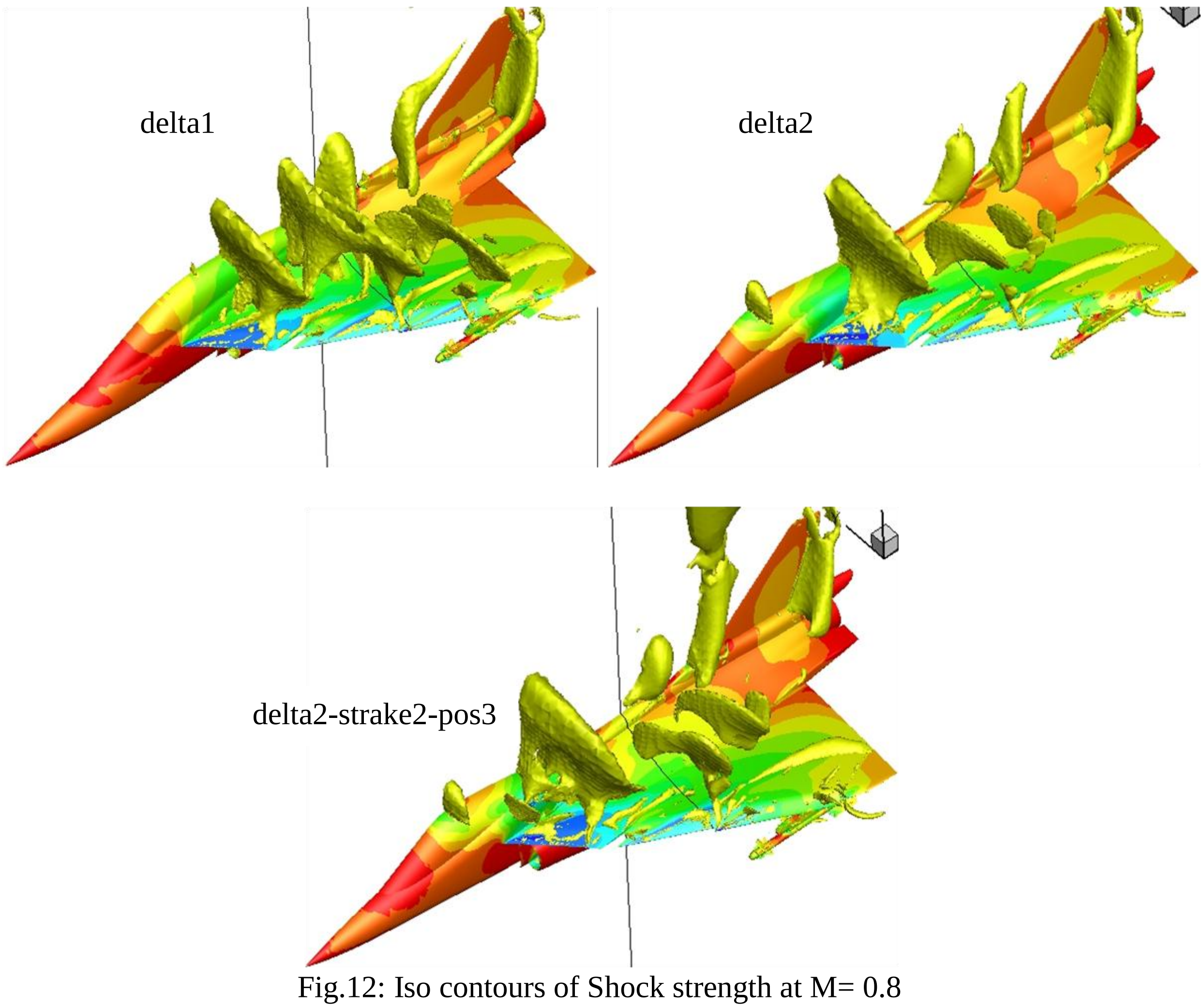

Fig.12: Iso contours of Shock strength at M= 0.8

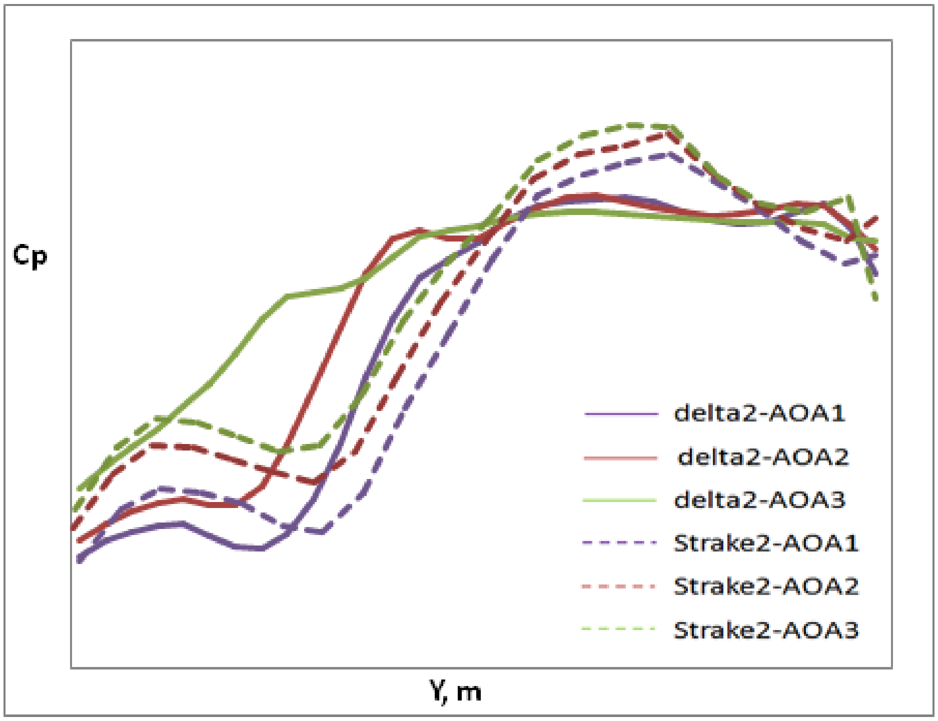

Fig.13: Surface Cp at forward of MRP

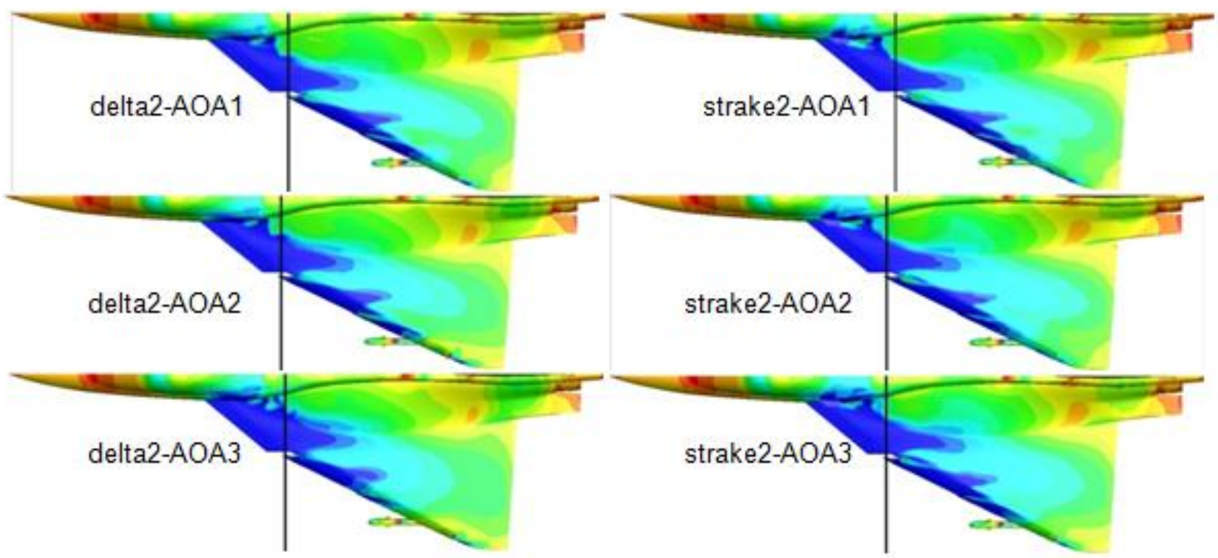

Fig.14: Cp contours at forward of MRP

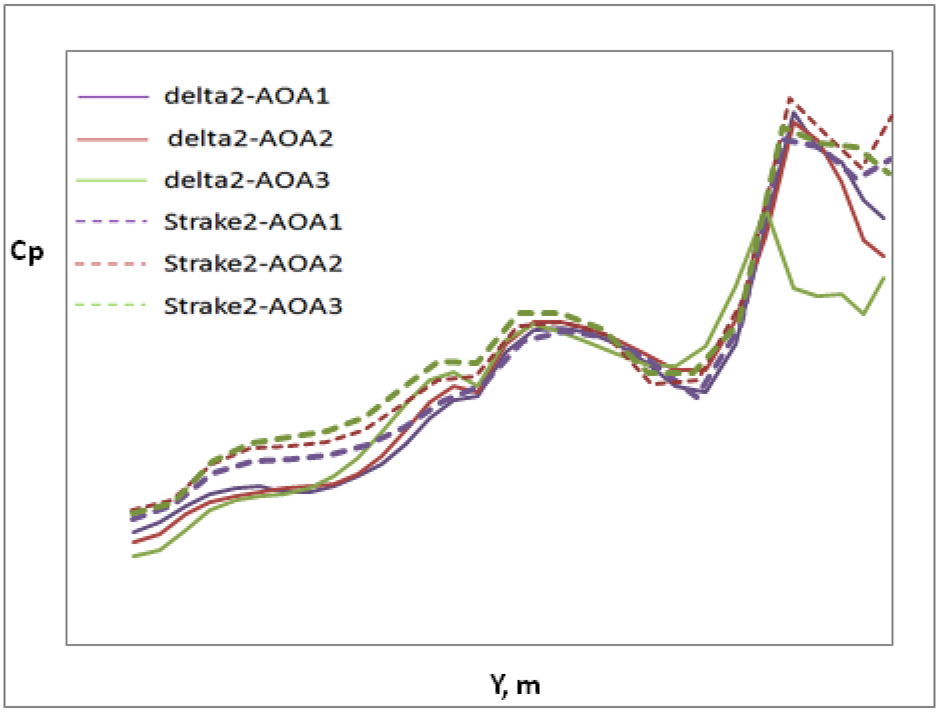

Fig.15: Surface Cp at MRP

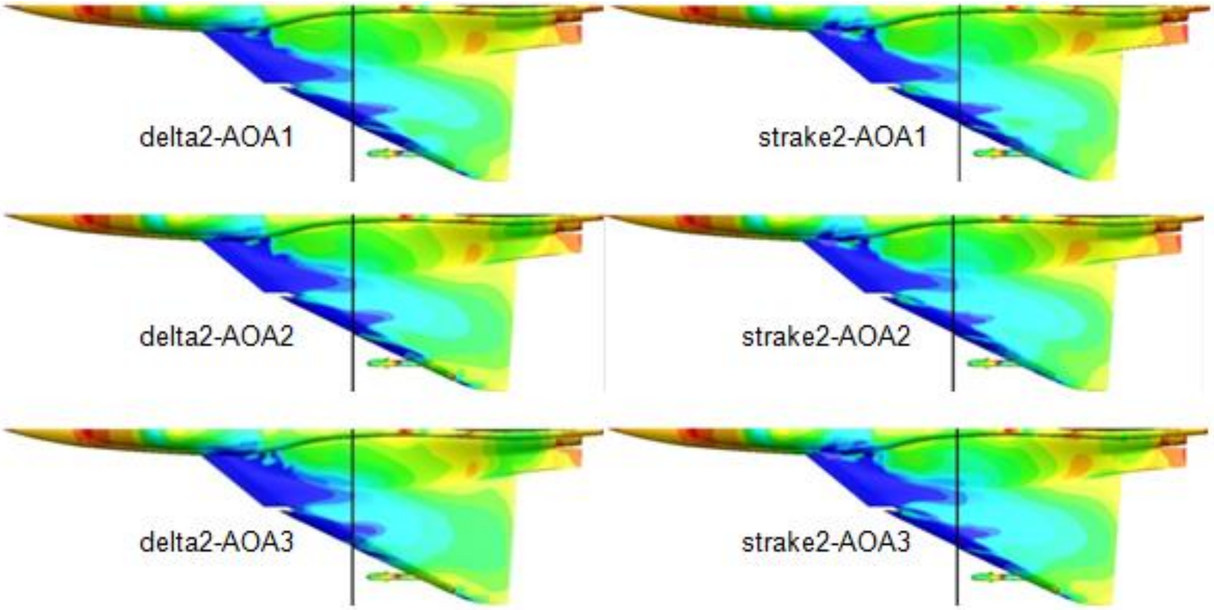

Fig.16: Cp contours at forward of MRP.

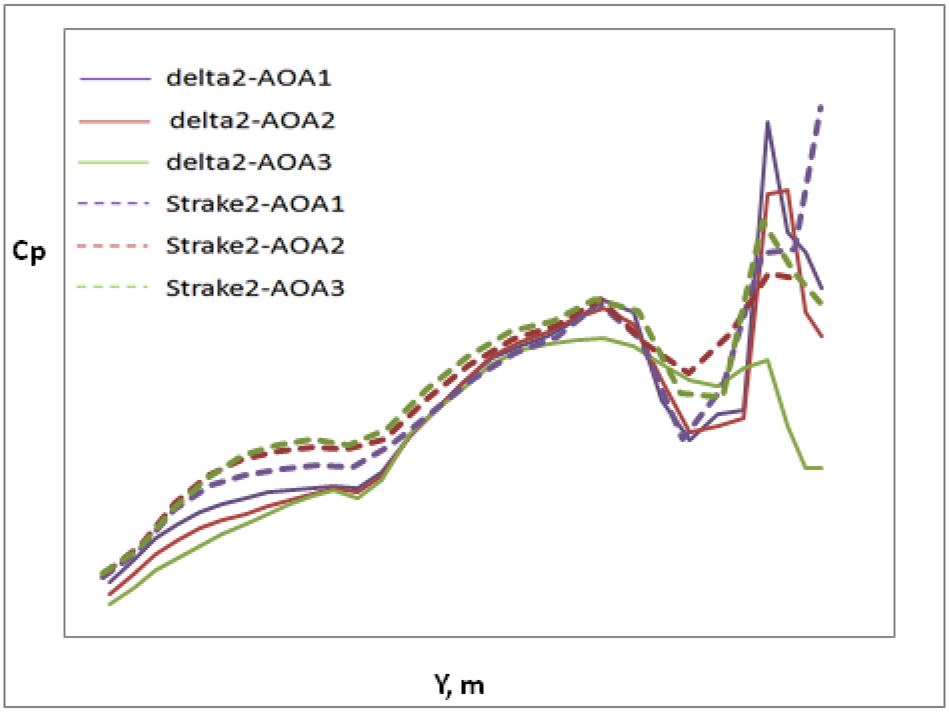

Fig.17: Surface Cp at aft of MRP.

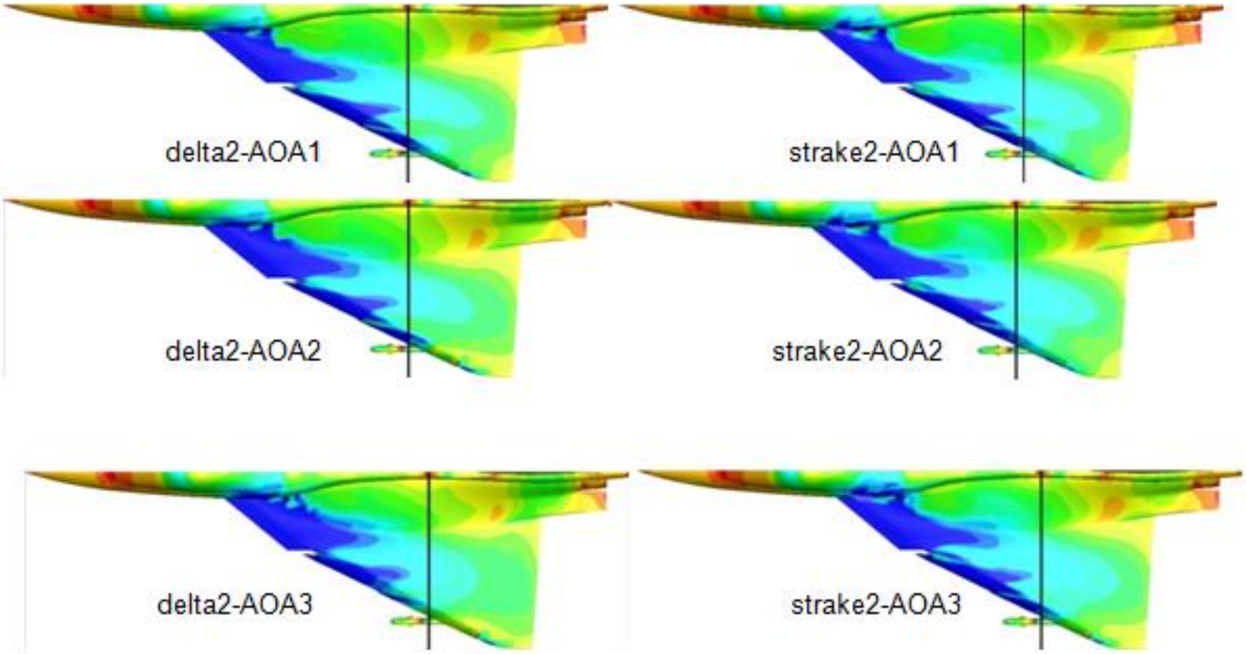

Fig.18: Cp contours at forward of MRP.

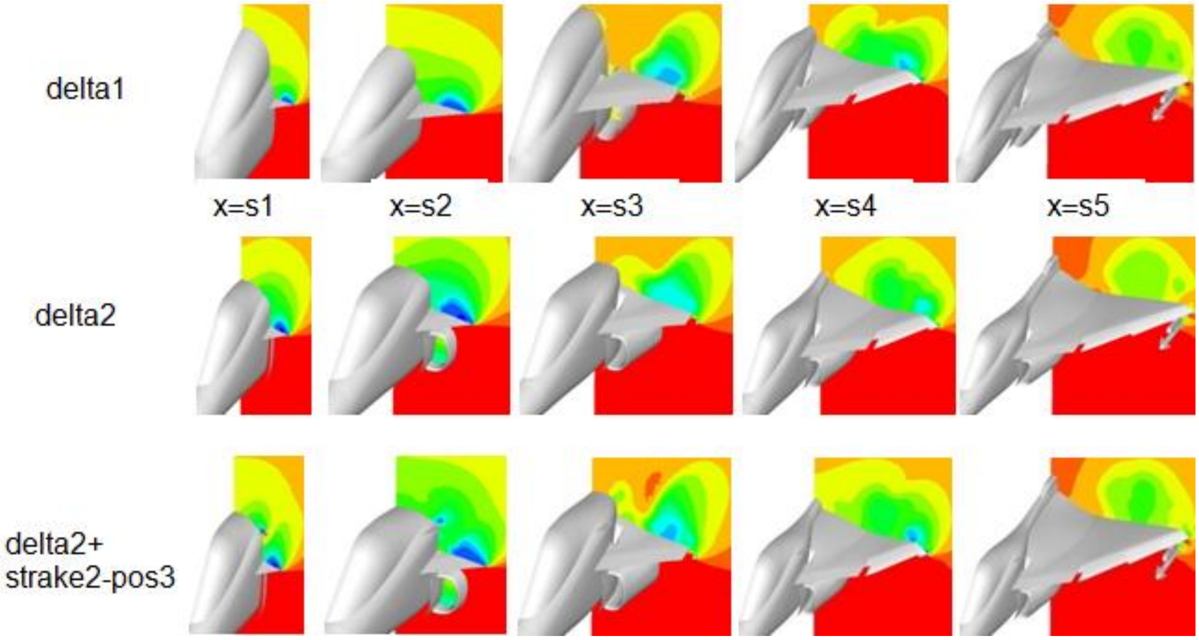

Fig.19: Section Cp Contours along length of the fuselage

6. CONCLUSION

- Detailed CFD investigations have been carried out towards achieving transonic pitch-up delayed to high AOA and with reduced severity on delta2 configuration, by introduction of passive strakes on the front fuselage. An attempt is made to understand the root cause of vortex breakdown, flow separation and shock interactions which cause this phenomenon. Based on the present studies, the following conclusions can be derived.
- Wind tunnel of delta1 were used for calibrating and validation of the CFD tools. While the overall trends are captured, there are differences in CM0, AOA at which pitch-up occurs and (dCM/dCL)max while (dCM/dα)max has a better match. CFD also over-predicts CL at high AOA. Even with these differences, CFD analysis is considered meaningful to shortlist shapes, sizes, locations and orientations of strakes for further experimental investigation.
- Delta1 experiences multiple weak shocks at M=0.8 and high AOA, and thereby pitch-up magnitude is lower as compared to delta2.
- Delta2 baseline configuration, experiences a strong shock in the stub-wing region which restricts downstream travel of the vortex flow. This Shock-Vortex interaction creates higher suction ahead of the MRP and contributes to early pitch-up.

- Introducing Strake 2(pos 3) on delta2 helps to reduce the shock strength near to the wing surface due to additional flow vortices. As a result, the vortices travel further downstream towards the wing leading edge creating additional lift in the aft region. This reduces the severity of transonic pitch up and delays it to higher AOA.

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8. REFERENCES

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