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Analysis of Vortex Dominated Flow Over Double Delta Wing

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Abstract

The maneuverability of fighter aircraft designed using double delta wing configuration at low subsonic speed in addition to under high angle of attacks are highly appealing and fascinating to comprehend. Flow pattern formed by double delta wing help to facilitate lifting force under high angle of attack and at such low subsonic speed. In comparison to delta wing, vortex formations by strake part of wing play an important role to create a persistent vortex core capable of delaying stalling. In this investigation, force coefficients of 75°/45° double delta wing configuration is extracted both from wing tunnel experiment and numerical calculation between 0° to 30° angles of attack at Reynolds number of 1.4×10^5 *based on root chord length. It has also been attempted to investigate the flow pattern formation over wing leeward surface, interaction between vortices formed by strake/wing based on Q-criterion and pressure distribution along propagation path of vortices obtained from CFD (Computational Fluid Dynamics) calculations. Implications of interplay between vortices and pressure distribution in lift generation have also been analyzed. It has been found that around 15° angle of attack strake and wing vortices merge and gets more intensified. With higher angle of attack the lift generation significantly diminishes because of vortex bursting.*

Keywords: *Lift and Drag Coefficient, Pressure Distribution, Q-Criterion, Strake, Vortices, Wind Tunnel, Wing*

1.0 Introduction

The primary requirement of fighter aircraft has always been the highest possible manoeuvrability to achieve effectiveness and accuracy under combat scenarios. These improvements in abilities of fighter aircraft have been achieved through various trials and errors. Backward swept and delta wing with sharp leading edge are the most notable implementations of wing design in modern aircraft. All these modifications have been done to mitigate limitations of conventional wings, while operating under moderate to high Angles Of Attack (AoA). Since 1920's after the inception of aircraft aerodynamic performance and propulsion mechanisms have been exponentially improved. Recent times effectiveness of fighter aircraft requires them to execute several manoeuvring acrobatics under subsonic speed and high AoA. Complex aerodynamic interaction of several parts in modern aircraft at a high angles of attack pose a serious challenge to designers and engineers alike even at preliminary stages. In order to comprehend the flow physics simplified wing configurations are analysed nowadays to study aircraft aerodynamics.

Wing configuration containing highly swept delta wing attached in front portion of comparatively smaller swept delta wing is noted as double delta wing. This wing configuration ruminate characteristics of swept main wing in conjunction with Leading Edge Extension (LEX).

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In case of delta wing configuration most notable energy transfer dynamics above the wing popularly noted as Rolled-up Vortex (RuV). Rolled-up Vortex (RuV) depart behind lifting or delta wings in form of trailing edge vortex wake. Rolled up shear layer facilitate formation of core region in free vortices' wake along with highly rotating inviscid fluid in outer layer of vortices'. It is also well known for the sake of generating the vortex interaction between wing upper and lower surface are necessary. For delta wing these vortices help to yield very low-pressure levels below the vortex cores over wing leeward surface and hence result in increase of lifting force. This lift created because of vortex is called vortex lift.

The flow features over double delta wing is similar in nature with delta wing configuration but with added complexity owing to addition of strake portion. At low AoA ($\alpha < 10^0$) vortex generated along leading edge of strake is known as inner or strake vortex. Concurrently another vortex initiating from strake/wing junction alongside wing leading edge is named wing vortices'. In case of high AoA ($\alpha > 10^0$) two separate vortices' over double delta wing configuration initiate to merge into a combined vortices'. Interplay of strake and wing vortices' stabilizes and energizes whole vortex mechanism, which correspondingly delays the vortex breakdown as well the loss off vortex generated lift over the wing. These non-linear interaction of vortices' makes prediction of aerodynamic performance of double delta wing difficult but it also make this configuration a lucrative field of study.

Cunningham and Dan Boer[1] experimented on a 76°/40° double delta wing control characteristics and stability problem at high incidence under flutter, dynamic response. Polhamus[2] developed theoretical model analogous to leading edge suction to further improve concept of vortex generated lift in sharp leading edge. Verhaagen[3] investigated about interplay between the vortex breakdown and AoA for 76°/40° double delta wing. Along with vortex breakdown discussion about flow separation and surface pressure distribution can also be found. Verhaagen[4] also experimented at LARC, NASA using low-speed wind-tunnel on effect of Reynolds numbers (varying between 05 to 1.5 million) for the flow over 76°/40° double delta wing within angles of attack ranging from -10° to 25°. Hebber[5] identified from water tunnel flow visualization study of double delta wing that coiling of vortices' occur earlier along with movement of vortex burst location with increase in angle of attack from 15° to 20°. The earlier promotion of vortices' coiling-up phenomena were also observed with modification in fillet without any perceived influence at high angles of attack for static condition. Sohn *et al.*[6] investigated the vortex interaction for the presence of centre-body in windward surface for 65°/65° double delta wing. The experiment was conducted at flow Reynolds number of (1.82×10^5) and (1.76×10^6). It was identified that up about 24° AoA the effect of centre body has very small leverage over wing leeward surface pressure distribution. Hayes and Smith[7] performed an extensive investigation of vortex generator in order to modify wing tip vortices. Hemidi and Rahimi[8] performed numerical analysis on 76°/45° double delta wing using Fluent. Sohn and Jang[9] observed from experimental investigation of double delta wing that combined effect of wing and strake vortex improves strength. It is also discussed that counter-clockwise coiling of the vortices' significantly diminishes with comparatively higher angle of attack. Sohn and Chung 6 studied the effect of variation in strake plan-form area to the vortex characteristics of double delta wing.

Ekaterinaris *et al.*[10] performed computational simulation to comprehend interplay between strake and wing generated vortices along with breakdown of vortices' while operating at high angle of incidence. The influence of fillets in order to control vortex shading, trajectory of vortex and subsequent breakdown of vortex in case of 76°/40° double delta wing were studied using RANS and Euler equation by Kern and Steven[11]. Majumdar and Saha[12] performed surface flow visualization at subsonic condition of 76°/40° double delta wing. Experimental results were also analysed alongside computational result. Inboard shifting of wing vortex along with outboard shifting of the strake vortex with increase in AoA was observed. Experimental and numerical investigation of flow field around 81°/45° double delta wing within AoA range of 0° to 30° under subsonic condition were discussed by Yuvaprakash *et al.*[13].

For the present study, in pursuance to comprehend vortex dynamics for flow over double delta wing algorithm of Q-criterion is implemented. In addition to three-dimensional vortex visualization utilizing Q-criterion pathline tracking development of circulatory flow, surface streamlines, velocity and pressure distribution at certain sections were also discussed. Hunt *et al.*[14] Hunt originally proposed characterization of vortex could be founded on decomposability of deformation tensor *u*. Indeed the deformation tensor *u* decompose into two parts (u = S +Ω), *viz*. symmetrical part *(S = 0.5(u + u^T))* defining strain rate tensor and anti-symmetric part () identifying rate of vorticity tensor (*T* in both equation signifies transpose). For the sake of Q-criterion to detect occurrence of dominant rotational effects or voritices' the value of *Q* required to be greater than zero *viz*., $Q = 0.5\left(\|\Omega\|_E^2 - \|S\|_E^2\right) > 0$, here $\|\cdot\|_E$ depicts the Euclidean norm where the rotational effects are prominent. Vivian Holman[15] leveraged on Q-criterion to differentiate vorticity magnitude Ω and rate of shear strain *S*. Muir *et al*.[16] analysed leading-edge vortex of 50° delta and swift wind-shaped delta wings in water flume within velocity range of 0.10m/s to 0.44m/s. Q-criterion analysis was utilized for detailed inspection of leading-edge vortex extracted from PIV experimentation. This present investigation aspire to visualize and study formation of complex vortex structures over wing leeward surface. Nature of lift characteristics with variation in angles of attack were also studied alongside the nature of vortices. It has also been attempted to prognosticate the behaviour of lift characteristic with change in vortices'.

2.0 Experimental Facility and Methodology

Experimental portion of the study is undertaken at open-circuit, suction-type, subsonic wind tunnel situated at Fluid Mechanics and M/C Laboratory in Department of Power Engineering, Jadavpur University, Kolkata. Detailed diagram of wind tunnel is shown in Figure 1.

2.1 Model Description

Wing model investigated in present study is tail-less 75°/45° cropped double delta wing configuration consisting of sharp leading edges. The detailed geometry of the wing configuration is shown in Figure 2.

2.2 Experimental Procedure

Experimental part of the study is carried out at free stream velocity 12m/s and Reynolds number based on length of root chord is 1.4×10^5. Lift characteristics of wing is measured utilizing strain gauge based three-component balance within 0 and 30 angle of attack range.

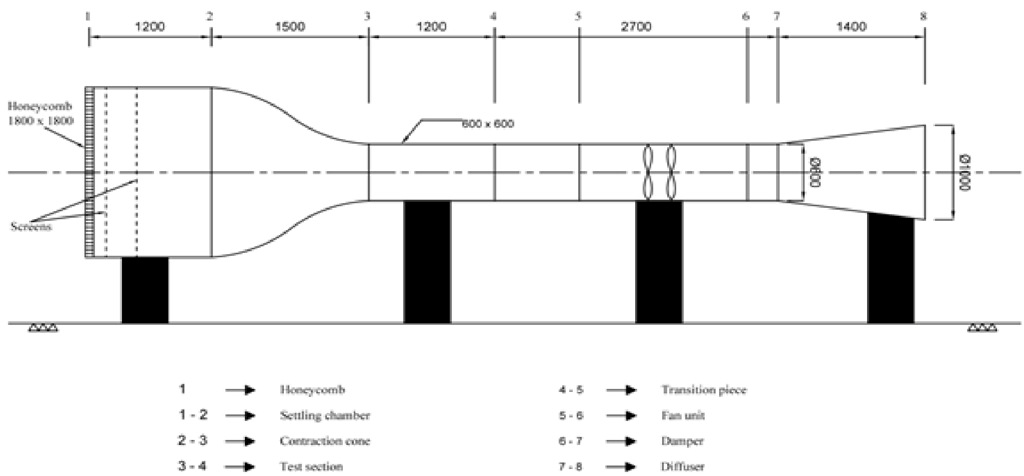


Figure 1. Schematic Diagram of Wind Tunnel.

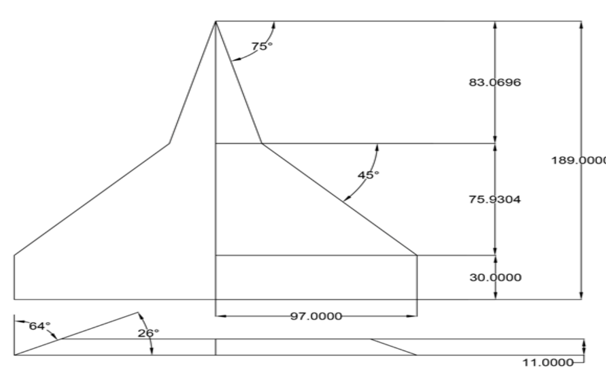


Figure 2. Geometry of Double Delta Wing.

2.3 Numerical Methods

CAD model of doubled delta wing having similar geometrical features according to specification given in Figure 2. Unstructured meshing hybrid of tetrahedron, pyramid and wedge are generated with the help of ANSYS meshing. Cross-sectional view of the produced mesh is given in Figure 3. Mesh sizes near the walls (average y^+ values of 1.7937) are organized properly to resolute the boundary velocity profile. Generated mesh consist of total 60975 no. of nodes for 234880 numbers of elements. Detailed statistics regarding mesh is given in Table 1. Spalart-Allmaras[17] turbulence model is utilized in couple with steady state solution are taken into consideration owing to the capability of Spalart-Allmaras model to predict result having reasonable accuracy without requirement of elevated computational power and time. Pressure velocity coupling method was employed in order to perform simulation. Second order spatial discretization scheme of solution is employed for the momentum. Inlet velocity direction was adjusted in order to simulate the required angle of attack. Convergence criterion of 10^{-3} is picked for the flow parameters residuals. Parameters that utilized for the prevailing simulations are shown in Table 2. Force coefficients calculated from numerical simulation were compared and found a qualitatively good agreement. For further visualization of three-dimensional vortex structure computationally generated results are analysed.

Several sectional planes are chosen along chord-wise direction in an effort to qualitatively study the surface pressure distribution and vortex visualization over double delta wing. These locations are x/c = 0.20, 0.16, 0.12, 0.09 and 0.04, where c is theroot chord of the wing model is given in Figure 4. These planes starting from close to crop section of wing are named A(x/c = 0.20), B(x/c = 0.16), C(x/c = 0.12), D(x/c= 0.09), E-sections (x/c= 0.04) respectively. The Q-criterion algorithm was utilized in conjunction with pathline and surface pressure distribution to qualitatively scrutinize vortical dynamics.

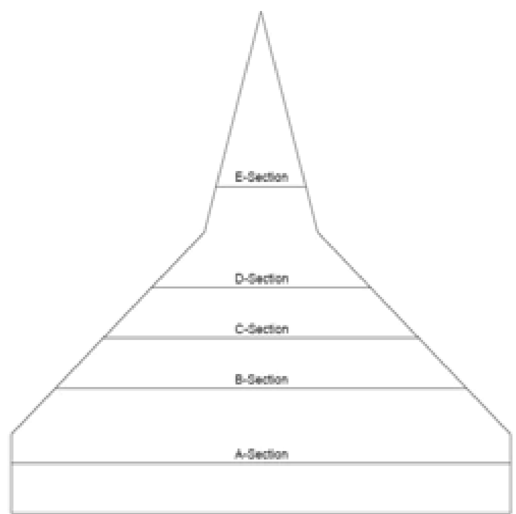


Figure 4. Locations of Measuring Sections.

Table 1. Statisitics of Mesh

Mesh Metric	Minimum	Maximum	Average
Orthogonal Quality	1.54e-002	0.99	0.9
Skewness	7.25e-004	0.98	0.3

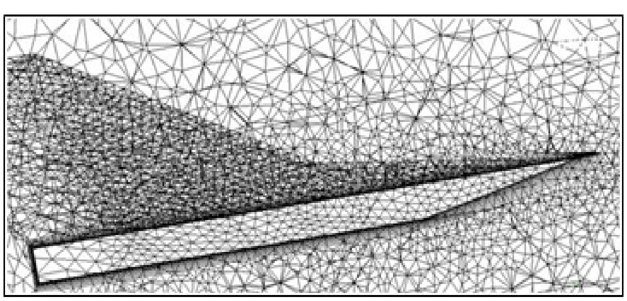


Figure 3. Cross-sectional View of Mesh Structure.

Table 2. Numerical Calculation Parameters

Gas	Air, Ideal Gas
Viscosity	1.846e-05 kg/m-s
Density	1.177kg/m3
M	0.04
Velocity	12 m/s
Temperature	300 K

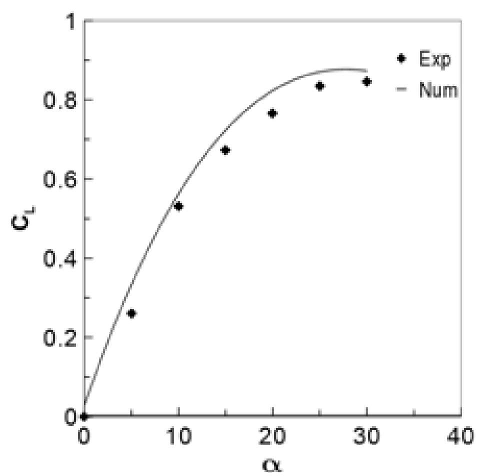
3.0 Results and Discussion

3.1 Lift Characteristics

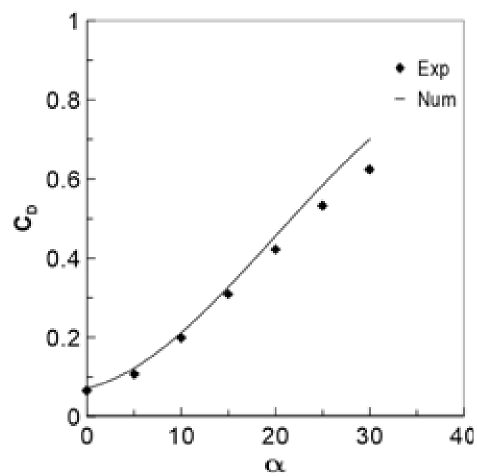
Figure 5a illustrates the distribution of C_L with respect to angles of attack (α). Initially it can be observed that C_L grows with increase in AoA. Upon scrutiny, it can be seen that the rate of rise in C_L upto 15° angle of attack is significantly higher in contrast to 15° angle of attack onwards. It can be noted from numerical results also that after 15° AoA the rate of increase in C_L diminishes. Figure 5b depicts the variation in C_D with respect to angle of incidence. Here also it can be seen that C_D rises with increase in AoA. But analogous to lift characteristics drag also appear to escalate at higher rate from at around 15° angle of attack. This rate of rise in drag might be linked to the loss of energy at vortex core and three-dimensional flow structure. This can be observed from both Figure 5 numerically calculated values remains in proximity of experimentally derived results. So it can be safely concluded that to further analysis of the flow field one can pursue using computational results.

3.2 Surface Streamline and Pathline

Figure 6 display path-line in combination with surface streamlines in wing leeward side obtained from numerical

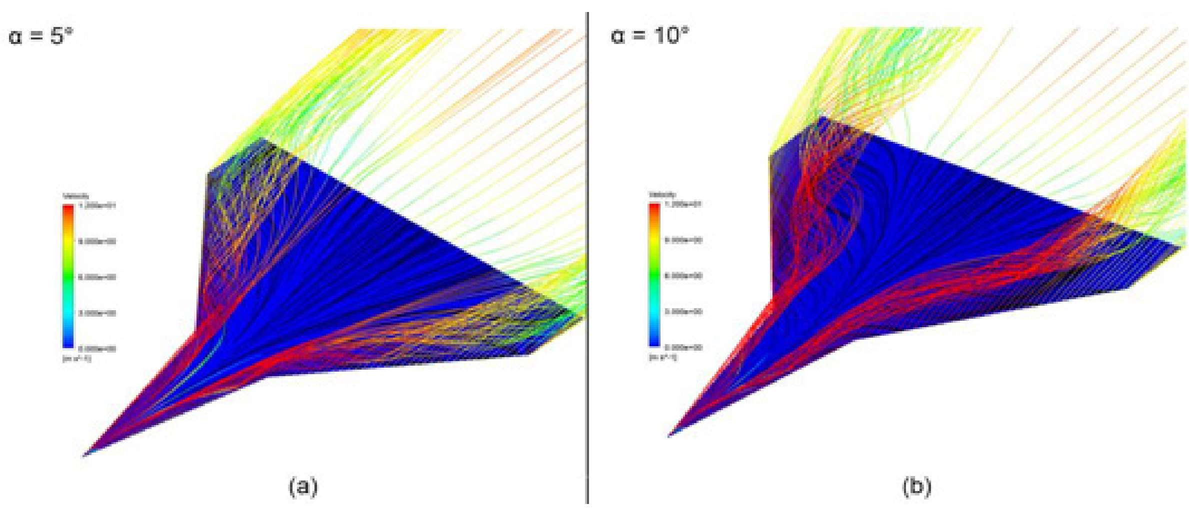


(a) Lift Coefficient vs. Angles of Attack.



(b) Drag Coefficient vs. Angles of Attack.

Figure 5. Force Coefficient vs. Angles of Attack.



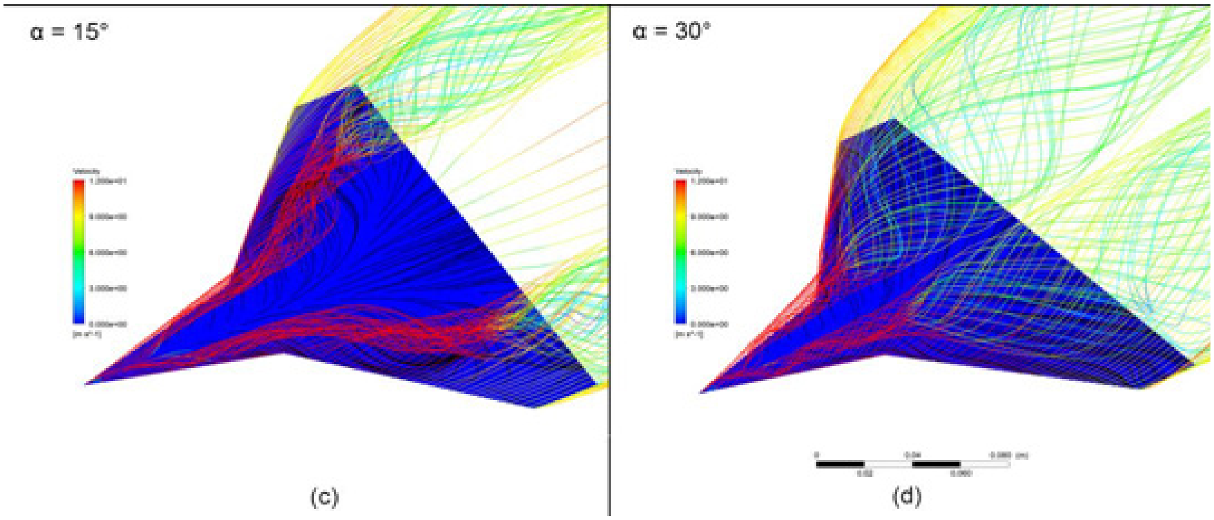


Figure 6. Surface Streamlines & Pathlines Plot.

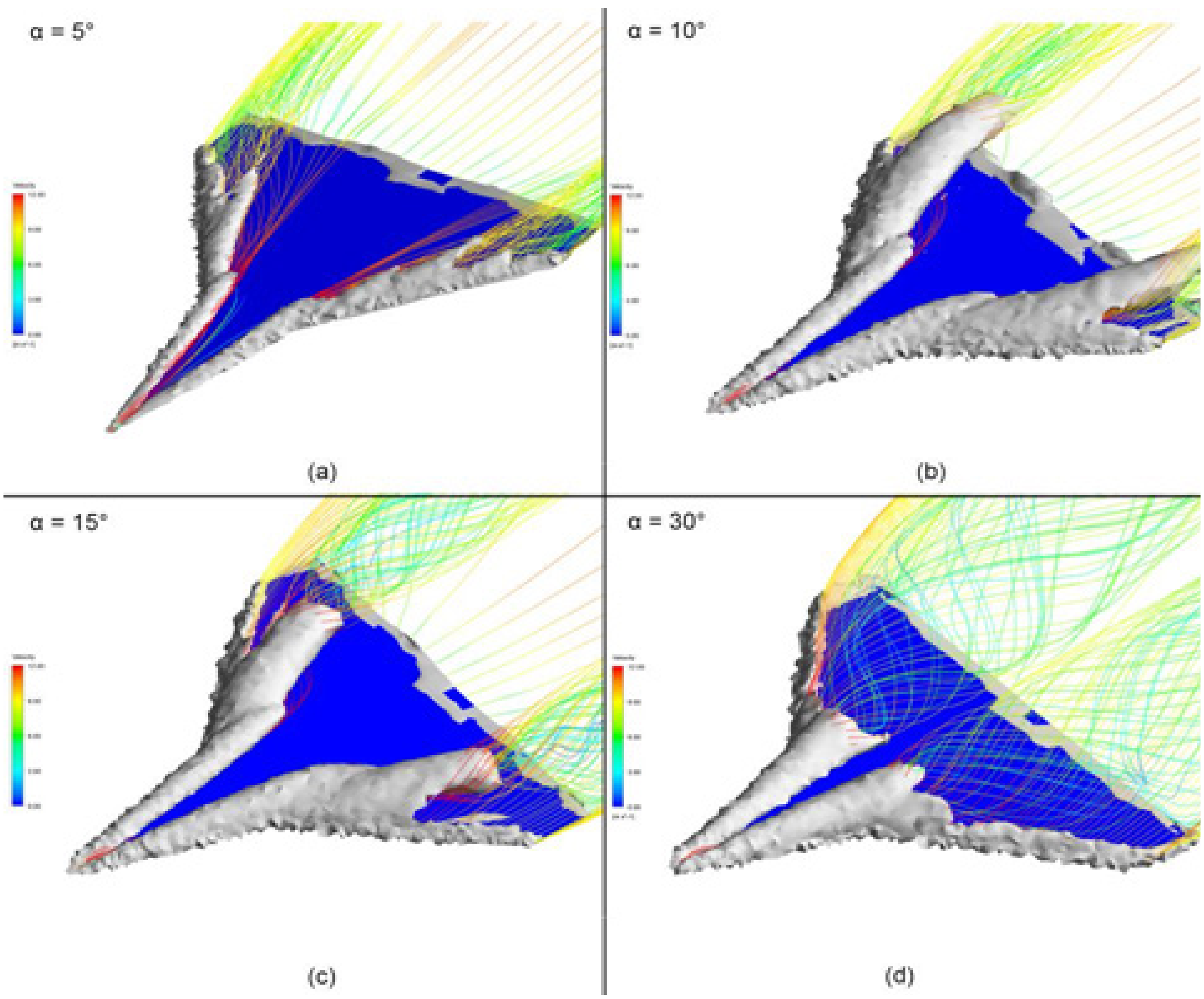


Figure 7. Q-criterion & Velocity Pathline Plot.

calculation. It can be observed from Figure 6(a) that at 5° angle of attack both strake and wing vortices lay close to leading edge of strake and wing respectively. But at 10° (Figure 6(b)) with increase in angle of attack, vortices appear to indicate slight outboard movement. Implication fo strake vortex seems to become more prominent at higher angle of incidence. Surface streamlines also indicate the orientation of flow. Fold in surface streamline suggest distortion in flow from streamlined direction. The course of surface streamlines in reverse stream-wise route hint at presence of circulatory/vortical flow of chaotic nature. At α =15° (Figure 6(c)) both wing and strake vortices' appear to merge over wing somewhere close to strake-wing junction. Here also it can be noted that wing vortices appear to shift towards inboard portion. At α =30° (Figure 6(d)) demonstrates that demarcation between strake and wing vortices disappear. Both wing and strake vortices become indistinguishable as consequence of merging. This intertwined vortices' rolls over the entire surface.

3.3 Numerical Vortex Analysis

Figure 7 depict the vortex visualization and provided with combination of Q-criterion surface and path-line. As mentioned before, path and propagation of vortex core is founded on Q-criterion analysis. Path-line are added for further elucidation. In addition, path-lines are coloured using velocity variable, where red colour indicate enhanced magnitude and towards green or blue colour present lower velocity. This visualization also provide clarification to the interplay between strake/wing vortices

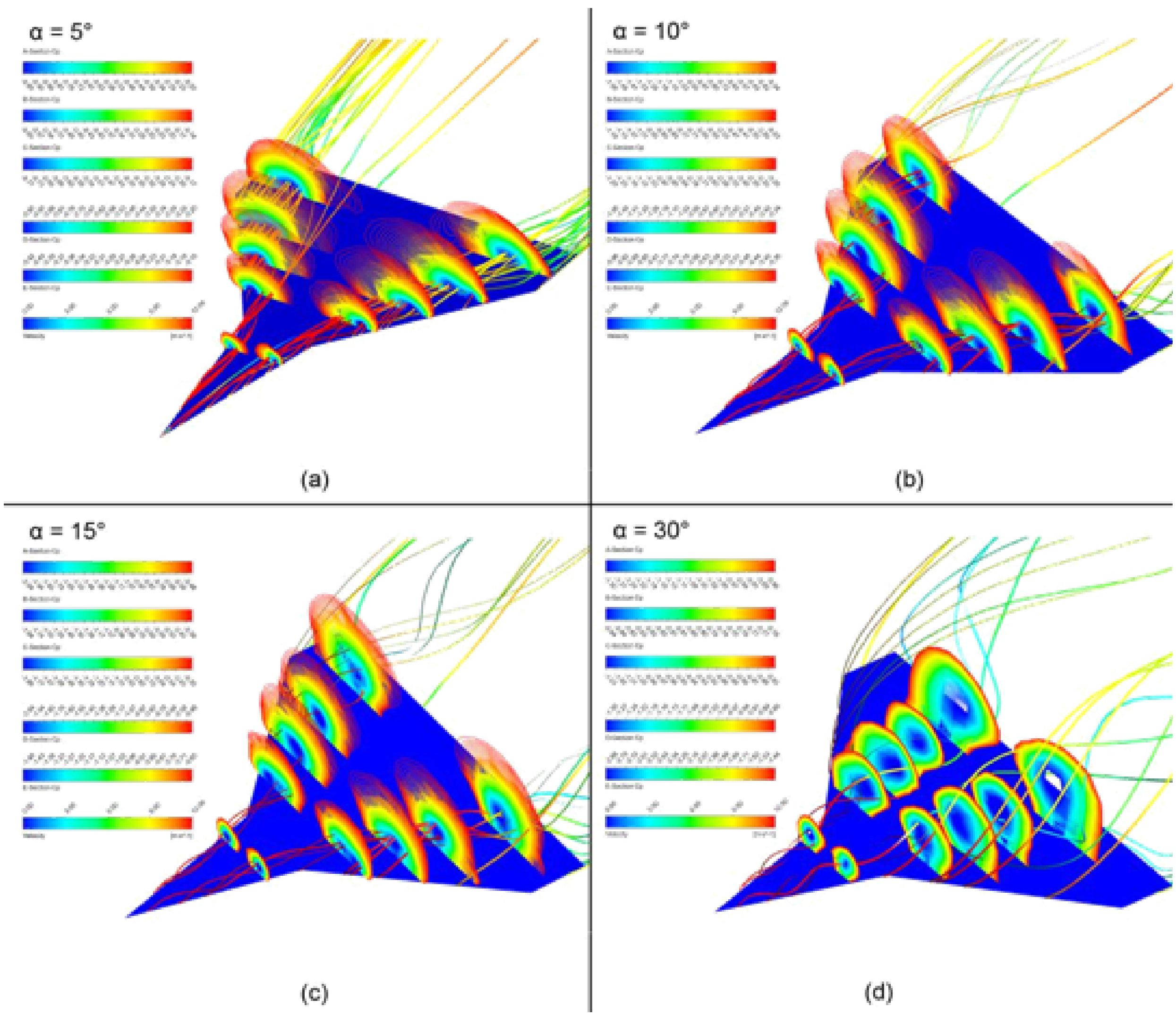


Figure 8. Pressure Coefficient Distribution at Sectional Planes.

and identification of vortex propagation path. From Figure 7, it can be seen that upto 10° angle of attack with increment in AoA both strake and wing vortex become more prominent, which indicated by incresed surface area of Q-criterion. Clear distinction can be made between strake and wing vortices. But in case of angle of attack 15° the demarcation in between strake and wing vortices' diminish close to strake/wing junction (D-section), appear as a merged surface from Q-criterion plot. In 30° angle of attack wing vortex appear to lose its strength after a certain distance indicating disappearance of Q-criterion surface. Upon scrutiny, it can also be observed that path-line colour seem to indicate that flow loses its velocity over wing surface between C and D-section at 30° AoA. Furthermore, to grasp the pressure coefficient variation along the vortex path pressure coefficient (C_p) contours are plotted in different pre-determined section along the path-line, which is shown in Figure 8. Here also the path-lines are coloured utilizing velocity magnitude. It can be seen from Figure 8 that with increase in angle of attack low pressure zone close to centre of vortices seem to shift inboard. This low pressure vortex core result in generation of lift over the double delta wing.

3.4 Pressure Coefficients

With the purpose to fully comprehend surface pressure distribution over section planes the pressure coefficient variation along span-wise direction close to leeward surface for every single sectional plane is extracted and plotted in Figure 9. Pressure distribution in different planes are plotted as C_p verses *y/s*, where *y* is direction along span-wise direction staring from root chord position or symmetry of the wing and *s* is local span of the sectional plane. Both are non-dimensional properties. In Figure 9 row-wise plots depict different sectional planes. Starting from bottom most row indicates A-section to top most being E-section. Additionally, column-wise plots represent different angle of attack under study. Here the left most column indicate 5° AoA and in increasing order the right most represents 30°. Elevated negative pressure peaks in distributions reflect the position of vortex core. An idea about intensity of vortex core can also be gained through magnitude of negative value in pressure distribution. Higher negative value of pressure imply greater intensity of vortices' which in turn tend to increment of lift force for double delta wing. For 5° angle of attack existence of strake vortex can be seen in E-section and starting from D-section wing vortex also seem to appear. It can also be assumed that wing vortices plays a significant role in lift generation at 5° AoA. Wing vortices diminish in the vicinity of A-section located in crop portion of wing. Upto 15° angle of incidence it can be observed that magnitude of negative pressure get elevated for both strake and wing portion. At greater angle of attack participation of strake vortices get stronger in lift generation.

At 15° it can be seen that section positioned at both strake and wing portion appear to have negative pressure of similar magnitude. This indicates interaction of strake/wing vortices'. Strake vortex appears to perform major role in stabilizing and strengthening wing vortex. While, this interplay of vortices' demonstrate the advantage of double delta wing in comparison to single delta wing. For 30° angle of attack E-section located in strake portion displays most negative pressure compared to remaining sections, which point towards presence vortices.

For each section it can be observed that for E-section produces increasingly higher negative pressure and most strong vortices close to 30°. in case of wing section (D, C, B-sections) appear to have greater negative pressure with increment in AoA up-to around 15°. At 30° angle of incidence in D, C, B-sections pressure becomes less negative and distribution become flatter in nature, which indicate probable loss in energy of circulatory flow (vortex bursting) and significant loss in lift generation. A-section located in cropped portion of wing appears to have noticeable negative pressure for 10° and 15° angle of attack.

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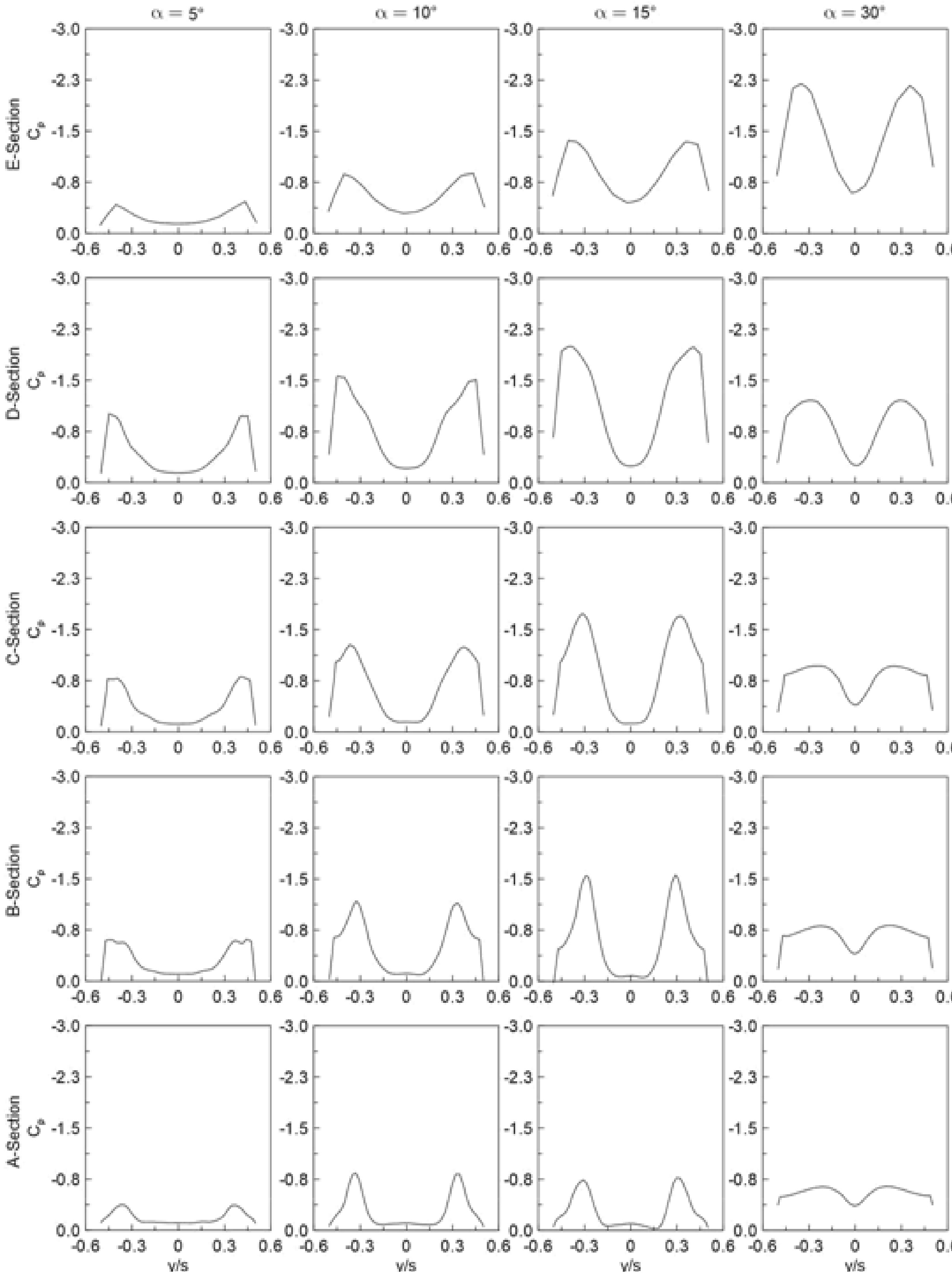

Figure 9. Plot of Surface Pressure Distribution at Different Sectional Planes and Angles of Attack.

4.0 Conclusion

In the present study e ect of pitching angles on the vortex behaviour and aerodynamic performance of a sharp edged 75°/45° double delta wing is studied qualitatively though a series of experimental and numerical analysis.

- On the basis of aerodynamic parameters it is observed from lift coefficient curve that double delta wing generate increasing amount of lift up-to about 10° angle of attack. Starting from the neighbourhood of 15° up-to about 30° AoA, it is seen to increase at a reduced rate compared to previous pace of increment.
- Post force analysis numerically calculated path-lines, Q-criterion in addition to pressure distribution at certain pre-determined plane along the vortices' are also analysed. Detailed qualitative trajectory of vortex is scrutinized utilizing Q-criterion. To further visualize and comprehend the vortex interaction and its effect on force parameters path-lines coloured using velocity and surface pressure distribution at several predetermined sectional planes are also analysed. It is observed that with increase in angle of attack strength of both strake/wing vortices increases with marked increase in negativity of surface pressure at 5° and 10° AoA. At 15° it is noted that both strake and wing vortex seem to be merged post wing strake junction. Here the wing vortex appear to be strengthened and stabilized with the help of strake vortex as suggested by literature of double delta wing. For 30° vortices appear to lose its strength over wing surface representing burst and also significant loss in lift generation. Upon scrutiny, it can also be seen that with increase in angle of attack the location where vortex loses strength shift forward.

Numerical and experimental results showed reasonably overall acceptable agreement in connection to prediction of aerodynamic parameters. The numerical results are well justified by Spalart-Allmaras turbulence model. Computationally generated results are found out to vary within average of 15% from experimental value.

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Nomenclature

AoA	=	Angle of attack (degrees)
C	=	Model root chord (m)
C_P	=	Pressure coefficient
c	=	Local sectional chord (m)
CFD	=	Computational fluid dynamics
C_D	=	Drag Coefficient
C_L	=	Lift Coefficient
Exp	=	Experimental value
M	=	Mach Number
Num	=	Numerical value
Q	=	Q-criterion value
RuV	=	Rolled-up vortices
S	=	Strain-rate tensor
S	=	Local span of wing
LEX	=	Leading-edge extension

Greek Nomenclature

α	=	Angle of attack (degrees)
u	=	Deformation tensor of velocity
Ω	=	Vorticity magnitude
y^+	=	Non-dimensional distance