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# 3D simulation and analysis of cropped delta wing vortex

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## Abstract

Simulation of vortex structures and studying their effects on the performance factors, is one of the most demanding stages in the aerodynamic design of flight vehicles. These chaotic flow patterns are more important for high maneuver delta wing aircrafts where the high attack angles are unavoidable. In such conditions a longitudinal vortex is always observed on top of the leading edge and plays a very important role in aerodynamic performance shifts and stability of flight vehicle. In this paper, the results of highly accurate three dimensional numerical simulation of cropped delta wing for investigating the vortex behavior, has been presented. For this study the Navier-Stocks equations have been solved by 24 computational nodes of cluster computer, in a 3D structural grid domains.

**Keywords:** *‘‘Wing vortex’’*, *‘‘Delta wing’’*, *‘‘High attack angle aerodynamics’’*, *‘‘Numerical simulation’’*, *‘‘3D wing structural grid’’*

## Introduction

Different areas of the aircraft design process rely on accurate estimation of the stall and flow separation on the wings and control surfaces. This includes performance analysis, determination of wing aerodynamic performance and highly accurate simulations. As an example, if autopilot of a UAV has been designed to prevent the stall situation in pitch, it requires to know exact stall angle. Such example can show the importance of aerodynamic simulations before any practical tests when the control systems are being designed simultaneously.

The subsonic flight and maneuvering abilities of aircrafts designed for low supersonic flight phase, are significantly affected by the existence of free vortices. At moderate-to-high angles of attack, the flow invariably separates from the leading edges of the swept slender wings, as well as from the forebodies of the air vehicles. Delta wings in different types generate and keep such vortical flow patterns on high angles of attack. Fig (1) has shown such phenomenon. These vortices form over the upper surface of the wing as a result of the roll-up of the vortex sheet shed from the leading edges. The flow induced by these primary vortices can separate near the wing surface due to the adverse pressure gradient the flow Encounters in the spanwise direction. This separated flow May then form an oppositely rotating secondary vortex, which Tends to move the primary vortex inboard and away from the wing upper surface. These secondary vortices can also form Tertiary vortices by the same process. The formation of these Vortices over delta wings has been demonstrated previously in a number of numerical solutions of the Navier-Stokes Equations [4, 5, 6, 15].

The leading-edge vortex at high angles of attack can faces a phenomenon called breakdown. The vortex breakdown is characterized by a sudden change in flow pattern around the core, and a decrease in the circumferential velocity associated with the rapid expansion of the vortex core. Typically, this process occurs over a distance on the order of the vortex core size and results in the vortex core transitioning from a well-defined vortical structure before breakdown to a more diffuse structure with milder velocity gradients and higher levels of turbulence after the breakdown. This phenomenon on an aircraft may result in several adverse effects, e.g., abrupt change in pitching moment, loss in lift, buffet, and so on, and can be a strict limitation of its maneuverability. Effects of the bursting may be felt not only by the individual aerodynamic surfaces on which the bursting occurs, but also on those in their close proximity. Realistic flow calculation about an aircraft at high angles of attack, therefore, requires an accurate prediction of vortex breakdown [4, 18].

In this paper the vortex structure and its core behaviors has been modeled and analyzed by a series of highly accurate CFD simulations on a cropped delta wing planform. The location of breakdown has been determined and its properties has been investigated.

## Geometry, Grid and numerical method

The geometry chosen for this study is a cropped delta wing with a leading-edge sweep of 43 deg. The fuselage is a basic cylinder-conid shape. The airfoil NACA 64A204 (root and tip) has been chosen for the wing. NACA 6-Series airfoil has some good advantages such as high maximum lift coefficient, very low drag over a small range of operating conditions and optimized for high speed. But poor stall behavior of this airfoil is a very important disadvantage that should be covered by wing design. Actually in attack angles more than 15 deg, the airfoil is stalled. The wing and fuselage have been shown in Fig (2).

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For the three dimensional CFD analysis, half of the structure, due to longitudinal symmetric plane, has been modeled by a fully structural grid with more than 6.4 million cells. Fig (2) has shown some sections of this computational domain. Three dimensional Navier-Stocks equation with SST turbulence model are solved by the pressure based method and coupled solver. Previous researches have proved the accuracy of this turbulent model for boundary layer analysis .According to the turbulence model, the Y+ value, less than unity has been used for the first grid point from the wall. The grid distortion problem for high curvature sections has been solved by using of low grows rate for grid (about 1.1). A cluster processor has solved the multiblock domains and the convergence was accepted when the residual reached 10e-5 for steady solver.

## Comparison factors

Although the vorticity definition and its cross sectional contours are always used for showing the vortex, other quantities are needed to study the vortex core. Static temperature, dynamic pressure and turbulent kinetic energy are the other basic factors in determining the vortex breakdown. The vorticity is the curle of velocity field:

$$\mu = \nabla \times v \tag{1}$$

The dynamic pressure q can be calculated by:

$$q = \frac{1}{2} \circ v^2 \tag{2}$$

And turbulent kinetic energy is:

$$\begin{aligned} &\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = \\ &-\frac{1}{\circ_o}\frac{\partial \overline{u'_i p'}}{\partial x_i} - \frac{1}{2}\frac{\partial \overline{u'_j u'_j u'_i}}{\partial x_i} + v\frac{\partial^2 k}{\partial x_j^2} \\ &-\overline{u'_i u'_j}\frac{\partial \overline{u'_i}}{\partial x_j} - v\overline{\frac{\partial u'_i}{\partial x_j}\frac{\partial u'_i}{\partial x_j}} - \frac{g}{\circ_o}\overline{\circ' u'_i}\text{¢}_{i3} \end{aligned} \tag{3}$$

According to properties of viscose flow, when the breakdown happens, the dynamic pressure (or kinetic energy) of gas will decrease severely along the core also this kinetic energy content of the flow in vortex, changes to heat therefore, the temperature should increase along the vortex core. Comparison between such factors can explain the properties of breakdown.

## Results

Fig (2) has shown the vortex structure in Mach 0.3 and a=15, the vortex core has been generated from leading edge close to wingroot. The lower kinetic energy part of boundary layer on the fuselage, has been separated from leading edge of wingroot and transformed to vortical flow motion. To find the vortex core location, the Eigen analysis algorithm has been used [20, 21]. For the better display a dense group of stream lines with red color, have been released close to core. These streamlines are recognizable in Fig (3) and (4).

In a=15 the vortex has enough strength to remain on wing from leading edge to trailing edge but with increasing the attack angle, the vortex core loses its strength and at a specified distance, the breakdown has happened. Fig (8) shows such a phenomena in Mach 0.3 and a=20.0. Vortex core suddenly has expanded and it cannot reach the trailing edge.

A comparison between the dynamic pressure variation and temperature, along the vortex core, has been performed in diagram (13) and (15). As it seen, the dynamic pressure has a sharp drop rate in a=20. The q can show the kinetic energy content of vortex core and when the drop rate is high, the breakdown is more probable. In the other word the q can show the vortex strength too.

Boundary layer on top of the wing has been affected by pressure distribution and vortex. Fig (5) has shown the surface streamlines (oil pattern) and movement of shear layer on the top of the wing. This patter can be an explanation for positive amount of shear force, 44.33 (N) in z direction (from root to tip). Because of relatively safe distance between expansion point and wing surface, there is no distortion in surface streamlines has been seen.

Although there is a difference in static temperature diagrams (Fig (15)), this factor is not completely suitable for comparison the vortex structures in low subsonic speeds. In such flight regimes the viscose effects and their interactions are very small therefore related losses are not effective. Such a definition is true for the total pressure too

## Conclusion

The vortex and breakdown phenomenon, has been observed clearly in Mach number 0.3 on the cropped delta wing by the numerical simulations. The Eigen analysis method can find the vortex core on top of the wing accurately because of mesh quality. Different flow factors has been measured along the core and the CFD Results have shown, the dynamic pressure changes rate can explain the breakdown phenomenon specifically. The location of breakdown on a delta wing is seen to move forward toward the wing apex with increasing angle of attack. The breakdown phenomenon has started in specified angle of attack and for Mach 0.3, this angle is about 20. The breakdown point has been shifted to the forward, with increasing the attack angle and the core expansion is heavier. Fig (8) shows the vortex structure for 25 deg. The breakdown point is close to wingroot and highly turbulent region on top of the wing has prevented the common locational flow separations.

Not only the exact aerodynamic design needs such a simulations, but also auto pilots and other control systems should be able to predict such distortions in vortex structure to prevent the aircraft from losing lift.

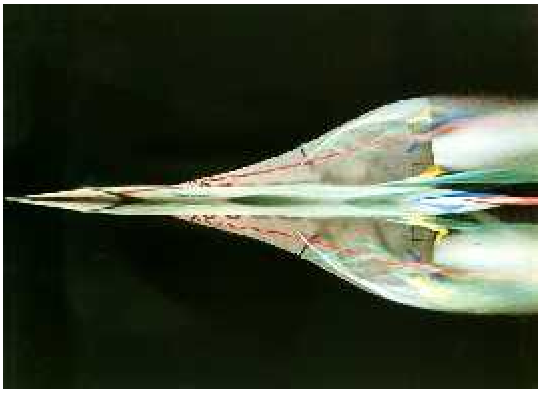

Figure. 1: Capturing flow of vector field and swirling behavior around the vortices [collage of engineering, university of UTAH], vortex on a delta wing (Concord) at high incidence.

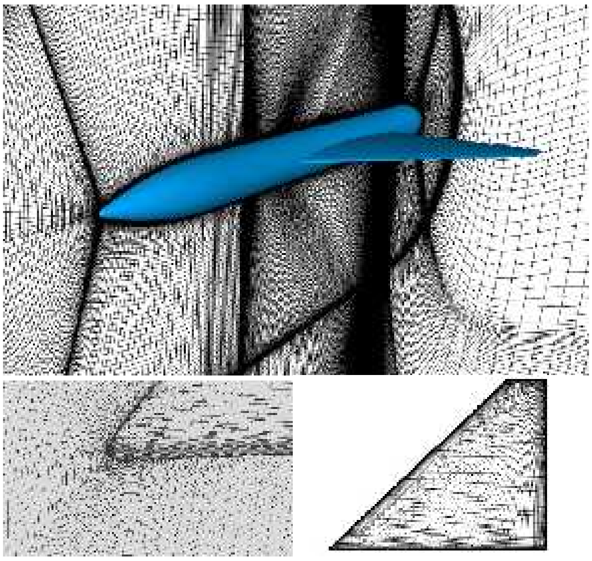

Figure. 2: Mesh sections.

Figure. 3: Perspective view of vortex structure, some streamlines are colored in black for better display.

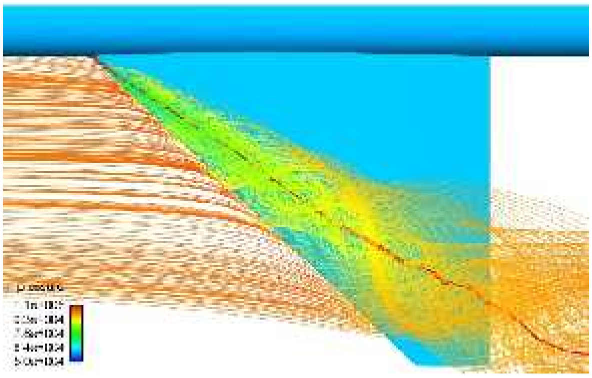

Figure. 4: Top view, vortex structure. Dense red colored streamlines in center of vortex show the core.

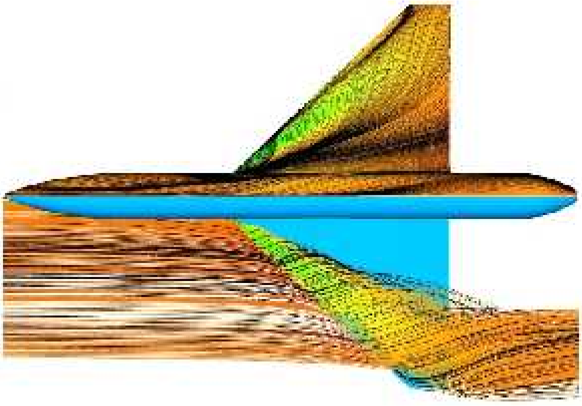

Figure. **5:** Surface streamlines (top) and vortex structure (down).

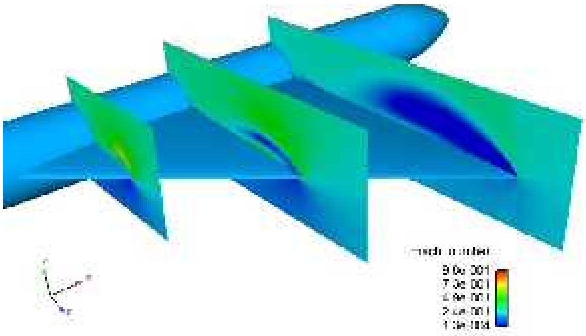

Figure. **6:** Mach contour in 3 different sections, 15 deg.

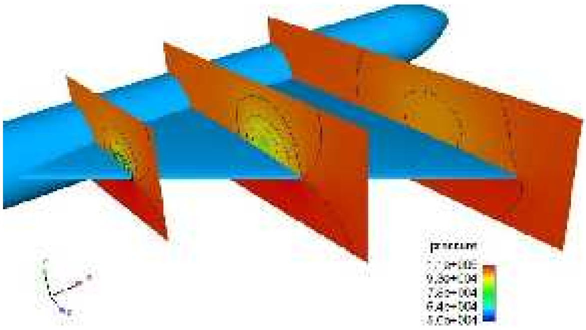

Figure. **7:** Pressure contours, 15 deg.

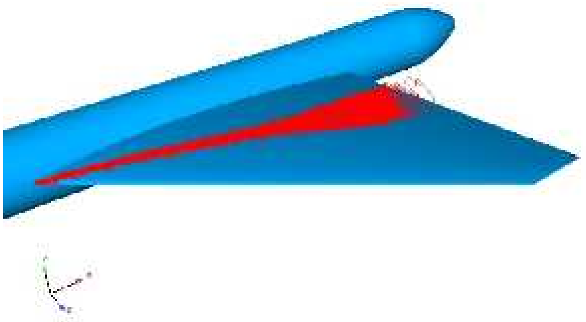

Figure. **8:** Vortex breakdown in 25 deg.

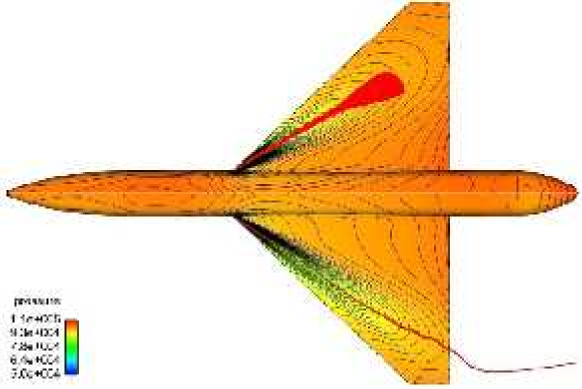

Figure. **9:** Pressure distribution and vortex cores.(top α=20° & dow α=15°)

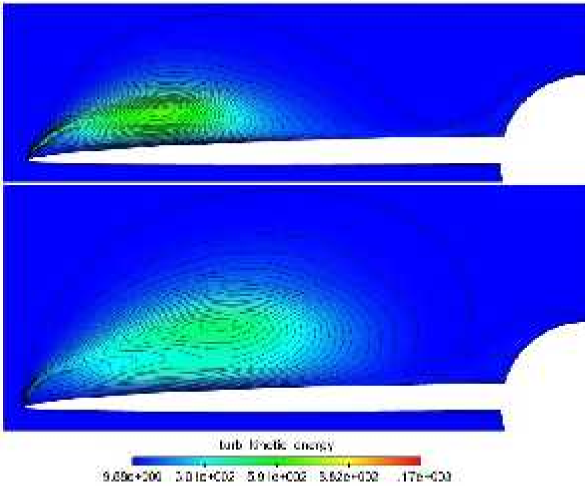

Figure. **10:** Turbulence kinetic energy contours in the same sections, sustain vortex (up), breakdown (down).

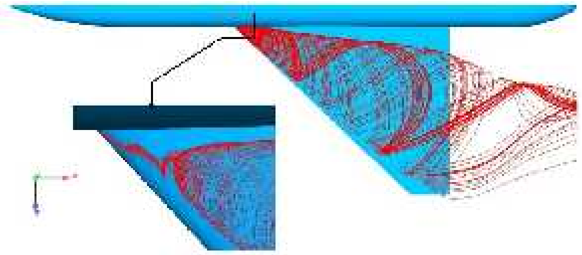

Figure. **11:** Vortex structure at 25 deg. The wing is close to stall and the breakdown point is shifted to the wingroot.

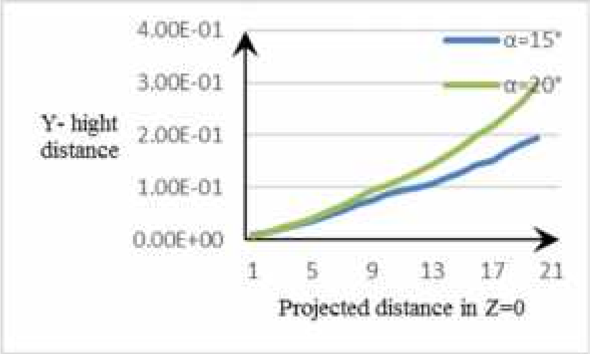

Figure. **12:**

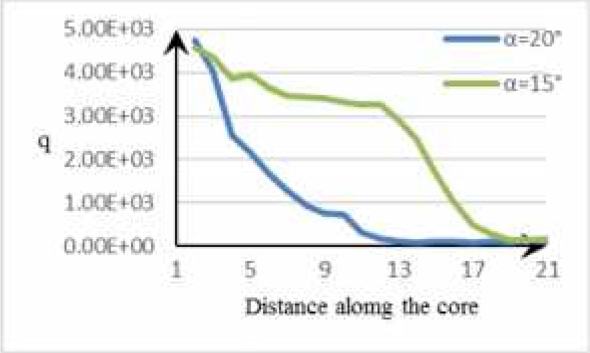

Figure. **13:**

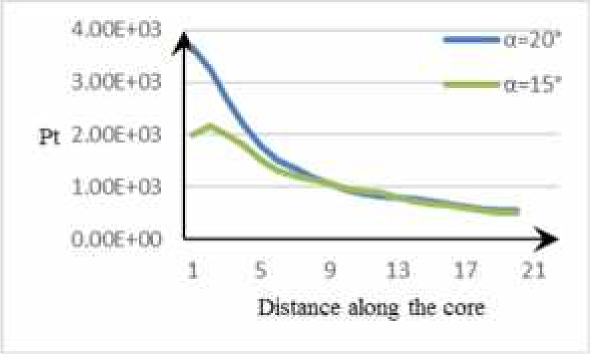

Figure. **14**

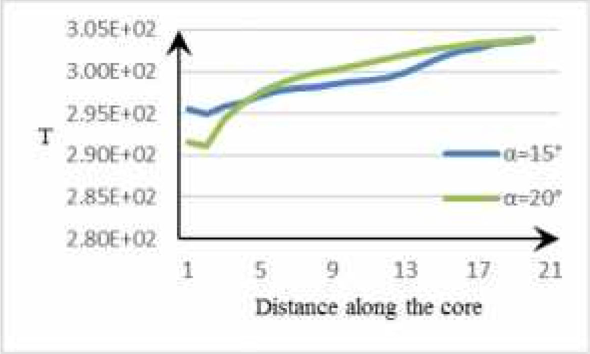

Figure. **15**

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