The Investigation of Crossflow Velocity and Off-the-Surface Streamtrace Topology for a Moderately Swept Wing at Transonic Mach Numbers

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(Abstract)

The purpose of this thesis is to investigate the crossflow and off-the-surface velocity traces on a moderately swept wing at transonic Mach numbers. Computational Fluid Dynamics (CFD) was used to generate the data used to visualize the flow field. This was done for angles of attack of 6, 7, 8 and 10 degrees at a Mach number of 0.8.

An overview of flow topology and singular point theory is given as a means to describe the flow field and describe the differences between it at various angles of attack. After performing an investigation of the crossflow velocity traces it was verified that the use of a line of separation in the flow topology as an indication for flow separation is a necessary condition. It was also found that the crossflow topology is more sensitive to shock location than to angle of attack.

It has been verified that a line of separation in the crossflow is an indication that separation may be present on the surface of the wing. Furthermore, shocks complicate the crossflow. In all of the cases the crossflow just aft of a shock becomes much more complex than it was before the shock. New singular points appear and interactions between singular points arise. As angle of attack is increased the flow topology changes critically only in the change from 6 to 7 degrees. This is the range in angle of attack in which a sudden shift in the location of the shock occurs, so it may be postulated that for this wing the flow topology is more sensitive to shock location as opposed to angle of attack. Comparing the topology between the 7, 8 and 10 degree cases, supports this hypothesis as the topology is similar before and after the shock for each case. The flow topology for each case fore of the shock is much different then the topology just aft of the shock.

The investigation of off-the surface traces has shown that as angle of attack is increased the area of separated flow not only grows but also becomes more complex. For

the 6 degree angle of attack case, the region of separated flow was concentrated near the surface and as one moved off the surface the flow quickly returned to the attached flow direction with no singular points. This was the case for the 7 degree angle of attack case only the flow did not reattach until after one moved approximately 0.25 feet off the surface. As the angle of attack was increased the distance off the surface in which the flow returned to moving in the downstream direction increased. Furthermore, as angle of attacked was increased the number of singular points and their intensity grew.

It was also verified that in all of the cases investigated the presence of a line of separation was an indication of separated flow. Moreover, in all but two cases there were two lines of separation. One located along the furthest outboard and inboard area of the separated region. No lines of separation were observed in or around attached flow, thus the lines of separation may not only indicate that separation is present but in fact give a location for the separated region.

Acknowledgements

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Without the assistance of the Interdisciplinary Center for Applied Mathematics, the post-processing and flow visualization would not have been possible. I am very grateful for their generosity in disk space and the time given to the assurance that I have the proper computing tools necessary to complete the flow visualization. I would also like to thank Darren Grove, from NAVAIR in Patuxent River, for his willingness to go out of his way to ensure that I have received the necessary data and understand where that data has come from. His friendless and experience have been a great asset to this work.

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Chapter 1 Introduction

1.1 Background

In the past twenty years, great advances in technology have led to significant advances in fluid mechanics. Computational procedures allowing aerodynamicists to investigate flows using complex three-dimensional computational fluid dynamics (CFD) to extract the flow topology are now widely available. Delery [ref 1] states that Legendre [ref 2] pioneered flow topology research by proposing that wall streamlines be considered as trajectories having properties consistent with those of a continuous vector field, the principal being that through any nonsingular point there must pass one and only one trajectory. This postulate implies that the singular points of the vector field can be categorized mathematically. Therefore, the number, type and relation between singular points can be said to characterize the pattern. Tobak and Peake [ref 3] took Legendre's work a step further using singular point mathematics along with bifurcation theory to define specific singular points in fluid flow topology along with their implications to the fluid flow. Since then, much research has been done on fluid flow topology, ranging from Chapman [ref 4] and Wang [ref 5] who classified flow topology for separation on three-dimensional bodies to Cipolla and Rockwell [ref 6] who investigated the instantaneous crossflow topology using particle image velocimetry.

The classification of three-dimensional singular points for flow topology has enabled aerodynamicists to successfully investigate, predict, and fix the separation phenomena alleviating adverse aerodynamic characteristics associated with separation. These classifications have been limited to surface and crossflow velocity traces of configurations with simple geometries. Classifications of off-the-surface and crossflow singular points for a swept wing have yet to be made and are the purpose of this thesis.

1.2 Approach

There has been significant recent interest in the complicated flow behavior that arises on modern fighter/attack aircraft wings after significant flow separation begins to occur. Thus an investigation of CFD solutions has been done. Solution files for a moderately swept wing at a Mach number of 0.8 for the angles of attack of 6, 7, 8 and 10 degrees were provided by the Navy and investigated. The grid, which consists of approximately 6 million points and 46 zones, was solved using the WIND [ref 7] code that uses Reynolds Averaged Navier-Stokes equations with the Shear Stress Transport (SST) [ref 8] turbulence model. The Reynolds number corresponds to an altitude of 15,000 feet. The solution files were used to calculate the pressure coefficient, and velocity vectors using the standard Plot-3D equations. The velocity vectors were then plotted to obtain plots of the off-the-surface and crossflow velocity traces using Amtec Tecplot version 8 [ref 9]. Figure 1 displays the wing which was investigated and shows exactly what was modeled.

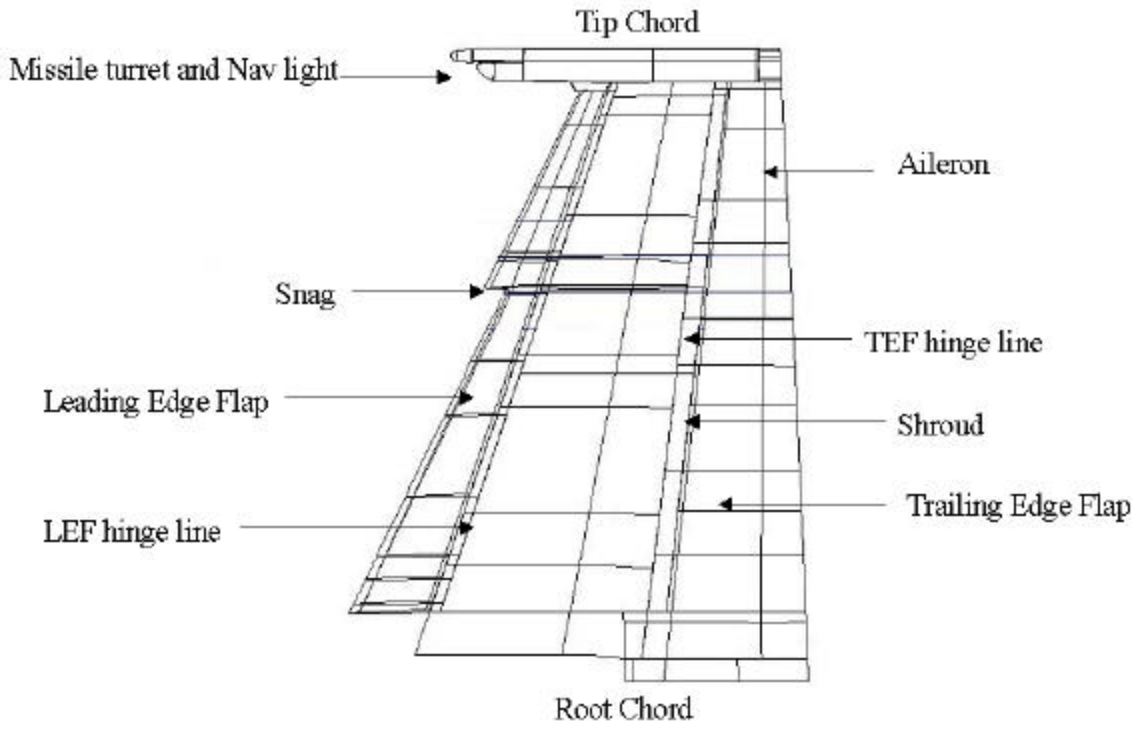

Figure 1. Wing Geometry and Definition

Off-the-surface velocity traces were constructed by extracting slices of the CFD files, which lie perpendicular to the crossflow and parallel to the horizontal surface at various distances off the wing surface. The velocity traces were then plotted on the extracted slice. Slices range from approximately one quarter of an inch off the surface to about 4.5% of the span. Singular points were identified and catalogued. Surface streamtraces were not investigated because the boundaries of each zone do not lie flush and Tecplot's streamtrace function will not plot the vectors between zones of this type.

The crossflow velocity traces were generated by extracting slices in the crossflow plane from the CFD files at various chord positions. Velocity traces were plotted on the extracted slice and the singular points were identified as well as catalogued. The catalogued singular points for each of the crossflow and off-the-surface traces were compared with all the cases studied.

Chapter 2 outlines the definitions necessary to describe fluid flow topology. The latter chapters contain the research and results performed in the attempt to correlate crossflow and off-the-surface flow topology.

Chapter 2 Fluid Flow Topology

2.1 Topology and Terminology

There has been much work done in the field of flow topology in the past twenty years. All of which confirms that the starting point is to consider a steady viscous flow over a smooth three-dimensional body where the skin-friction lines or streamlines on the surface of the body form a continuous vector field. One translates this vector field into a mathematical model in terms of the surface velocity, shear stress and vorticity vector components as documented in Tobak and Peake [3].

With the completion of the mathematical model, one must investigate where the magnitudes of the derived vector fields are identically zero. Such points in the vector field are called singular points. Singular points may be classified as two types: nodes and saddle points. The classification of nodes can be further divided into nodal points and foci, of either separation or attachment.

A nodal point is a point common to an infinite number of streamlines. If the streamlines converge to the nodal point, as seen in Figure 1a, it is said to be a nodal point of separation. Conversely, if the skin-friction lines diverge from the nodal point it is said to be a nodal point of attachment, seen in Figure 2b.

Foci differ from nodal points in that an infinite number of streamlines spiral around the node. If the streamlines spiral away from the node, as seen in Figure 2c, the node it is defined as a foci of attachment. Streamlines, which spiral into the node, seen in Figure 2d, are defined as foci of separation.

A saddle point may be defined as a singular point in which only two particular lines intersect at the singular point, each of which is in the direction towards or away from the singular point. All other streamlines miss the singular point and follow the directions of the adjacent lines that pass through the singular point as seen in Figure 2e.

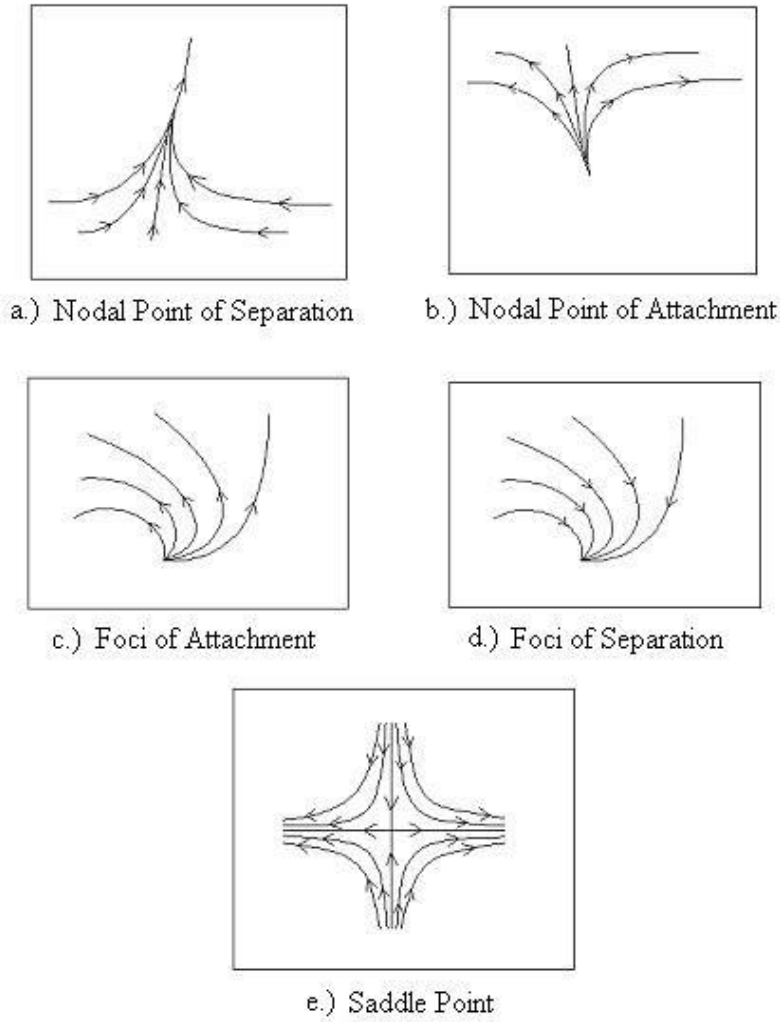

Figure 2. Singular Points - 2a. Nodal Point of Separation, 2b. Nodal Point of Attachment, 2c. Foci of Attachment, 2d. Foci of Separation and 2e. Saddle Point

Different combinations of nodal/saddle points and how they work together have received much attention by Tobak and Peake [3] and Chapman [4]. For the purpose of this paper, we shall only be concerned with the specific singular point interaction in which a line of separation emerges. A line of separation is present when the streamlines emerging from the nodal points of attachment are prevented from crossing by the presence of a particular streamline emerging from the saddle point as defined by Lighthill [ref 10] and seen in Figure 3. Most researchers agree that the convergence of streamlines on either side of a particular line is a necessary condition for separation however; it should not be used solely to define it as this may occur in other situations as well.

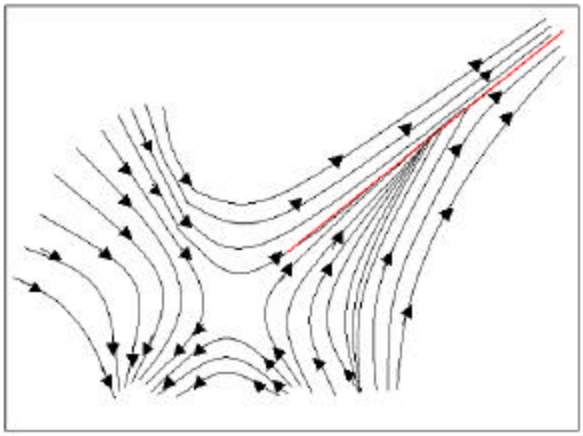

Figure 3. Line of separation

According to Tobak and Peake [ref 3], lines of separation may be further subdivided into global and local lines of separation. A global line of separation is a streamline, which emerges from a saddle point and leads to global flow separation. On the other hand, if a streamline not originating from a saddle point has other lines converging on it are defined as a local line of separation and leads to local flow separation. This terminology is not necessarily common amongst all researchers but will suffice for this paper.

2.2 Implications of Flow Topology

Singular Points acting in isolation or in combination fulfill certain characteristic functions that largely determine the distribution of skin-friction lines on the surface (Tobak and Peake) [ref 3]. A nodal point of attachment typically represents a stagnation point on a forward-facing surface, such as a leading edge of a wing, where as, a nodal point of separation acts as a sink where the skin friction lines that have moved over the body have vanished. Saddle points typically act to separate the streamlines from adjacent nodes.

When studying the topology of fluid flow, especially of separated flows, it is often useful to consider the change of topology as different parameters are changed. One might want to examine how the topology changes with angle of attack, Mach number, Reynolds number or possibly geometric changes. The bifurcations are those, which change the structure of the singular points in the vector fields. One applies bifurcation theory to study the changes in singular points with respect to parameters and investigate if new singular points appear, singular points change from attachment to separation or vise versa, or if singular points change from a nodal point to a saddle point.

Because the patterns of skin-friction lines and external streamlines reflect the properties of continuous vector fields, we are able to characterize the patterns on the surface and on particular projections of the flow. Hunt et al [ref 11] have shown that the notions of singular points and the rules that they obey can be extended to apply to the flow above the surface on planes of symmetry and on crossflow planes. Most recently Delery [1], discussed the collaboration of Legendre, a theoretician, and Werle', an experimentalist, in their pursuit to construct a theoretical tool allowing the elucidation of the structure of largely separated three-dimensional flows. In this paper, Delery discusses the implications of flow topology off the surface as well as reviews the work done in the flow topology field to date.

Chapter 3 Investigation of Crossflow Velocity Traces

3.1 Crossflow Defined

Flow which moves inboard, outboard and up off the surface of the wing. The velocity components in the vertical and spanwise directions, *v* and *w*, define the crossflow velocity. Tracing the crossflow and investigating it sheds light on the mechanics of the flow field which may not be seen or understood in the streamwise or surface planes. Such flow field mechanics may be vortices generated by a Leading Edge Extension (LEX vortex), tip vortices, snag vortex, inboard and outboard flow interaction, or vortex interactions.

Experimentally, little work has been done regarding the investigation of crossflow and separation in the crossflow. This is due to the complexity of probing the flow field off-the-surface without disturbing it. Simpson et al [ref 12] measured three-dimensional crossflow separation using laser Doppler velocimetry. This provided the most detail about the separation flow field but at great expense and with the limitation of requiring the knowledge of the separation line direction. Therefore, CFD is a common tool in the study of crossflows. Delery [ref 1] suggests that flow topology off the surface and in the crossflow may be insightful when investigating three-dimensional flows and separation.

3.2 Crossflow Grids and Data Generation

Amtec Tecplot was used to generate the crossflow grids and data. An imbedded Tecplot Slice function was used to extract 2-D planes out of the 3-D grid. The Slice function interpolates the data points in the grid to create a 2-D plane at a specified position on, in this case, the x-axis. Data for this grid, the v and w components of the velocity vector was calculated by dividing out the density from the momentum vector in the CFD solution files. Tecplot also has a streamtrace

function that allows the user to plot 2-D vectors. This was taken advantage of to plot the crossflow using the *v* and *w* components of velocity as the vector variables.

3.3 Definition of Streamwise Stations

With crossflow and its implications on the flow field addressed, it is necessary to investigate the crossflow velocity traces and their implications on the flow field in the vicinity of a moderately swept wing at a Mach number of 0.8. One must decide where on the wing singular points might appear and choose chordwise stations which will prove fruitful for investigation. This was done by comparing pressure coefficient contours, separation contours and investigating different flow field characteristics such as shock location, movement of the shock location and shock interaction.

Figure 4 shows the pressure coefficient contours for the wing at angles of attack of 6, 7, 8 & 10 degrees. The green and yellow areas indicate regions of low-pressure, which are close to zero. It can be observed that the low-pressure region grows rapidly with angle of attack. This is a possible indication of separated flow. These contours also show a jump in shock location. This is indicated by the light blue area in the 6 and 7 degree AOA cases jumping forward or 'pinching' towards the leading edge. Thus the area just before and aft of the light blue area would be good chordwise positions to investigate the crossflow because changes in the flow field due to shock location may have a major effect on the flow topology.

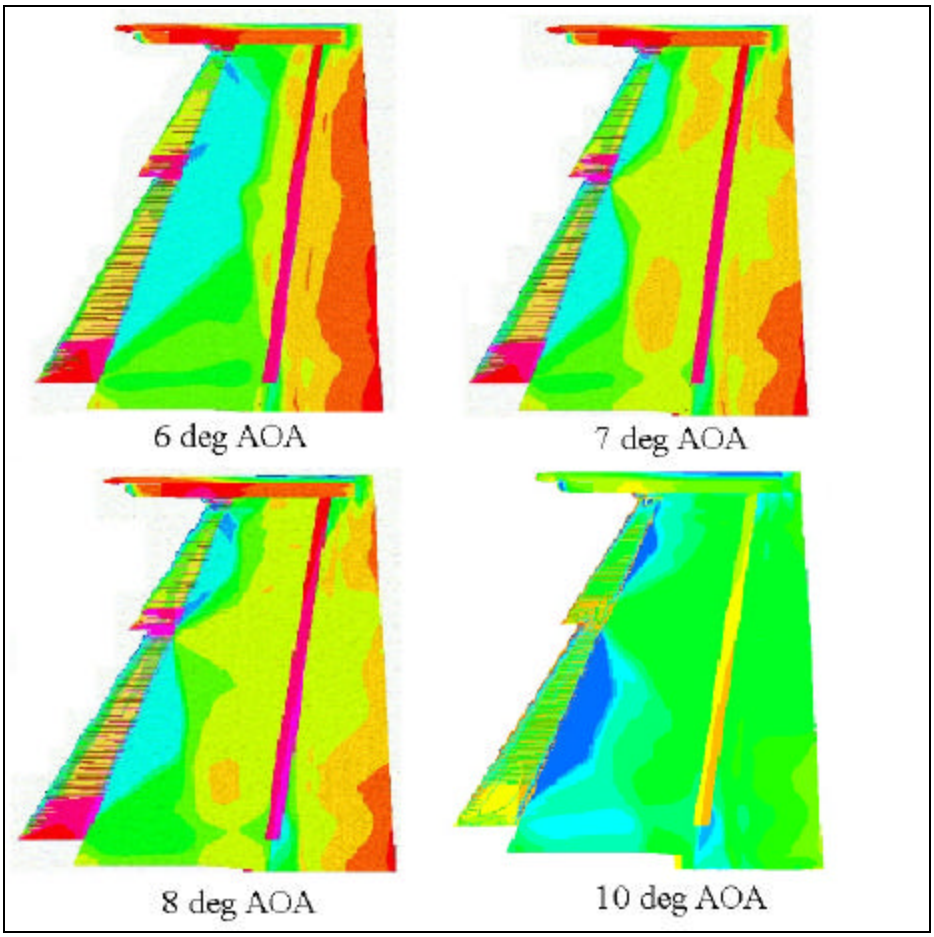

Figure 4. Pressure Coefficient Contours for 6, 7, 8 & 10deg AOA

Surface separation of the flow field can be indicated by a reversed or zero axial flow velocity. This can be used as a good preliminary tool for investigating if a flow field is separated or not. Figure 5 displays separation contours for the wing at each angle of attack. The blue region indicates positive axial velocity on the first grid off-the-surface where the red region is used to visualize the negative or zero axial velocity. As one might observe the area of separation drastically increases with angle of attack in the center portion of the wing. This area of separation is just aft of the pressure contour 'pinch', which indicates that there is a shock followed by separated flow. Since separation of three-dimensional flows and its topology are of great interest to aerodynamicists, this region will be investigated as well.

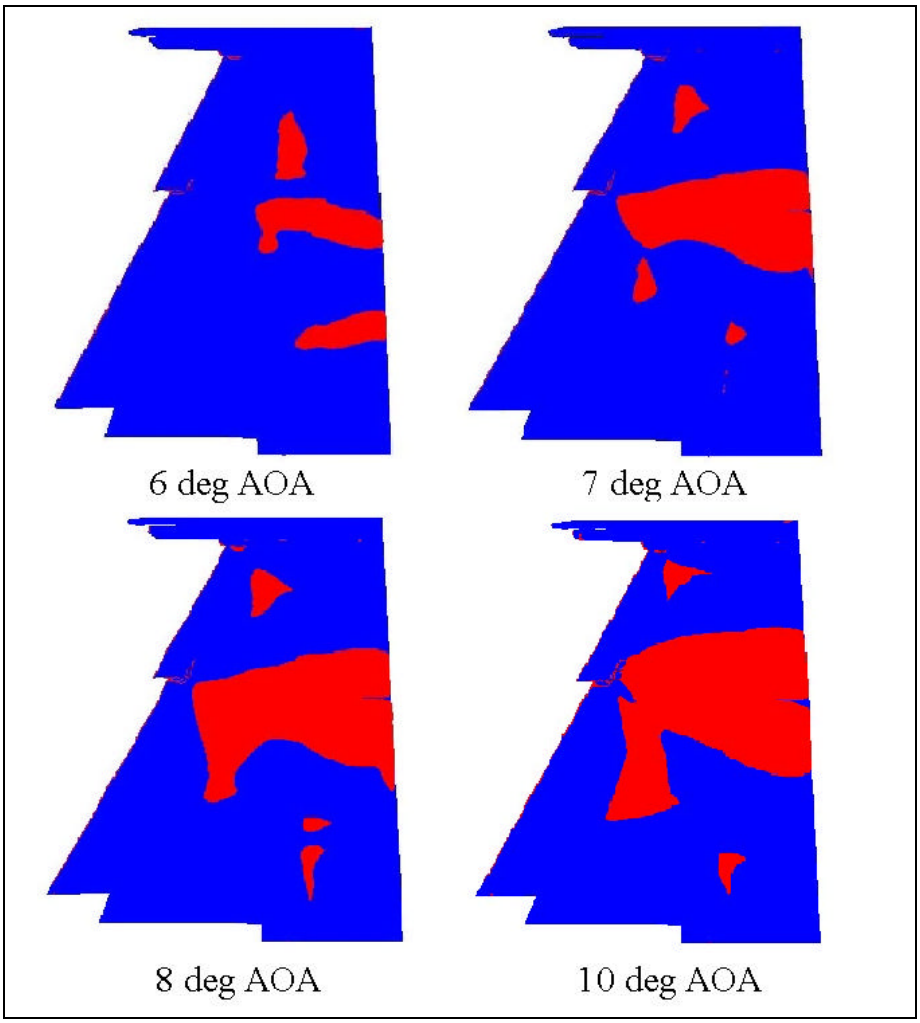

Figure 5. Separation Contours for 6, 7, 8 & 10 deg AOA

Shocks and their interaction with other shocks are also areas in flowfields which lack understanding. Figure 6 displays a pressure isobar for the wing at an AOA of 6 degrees. This isobar indicates that there are two oblique shocks and one normal shock present. These shocks are highlighted in red and the the interactions or merging of the them are circled blue. The interaction is where we will focus our attention.

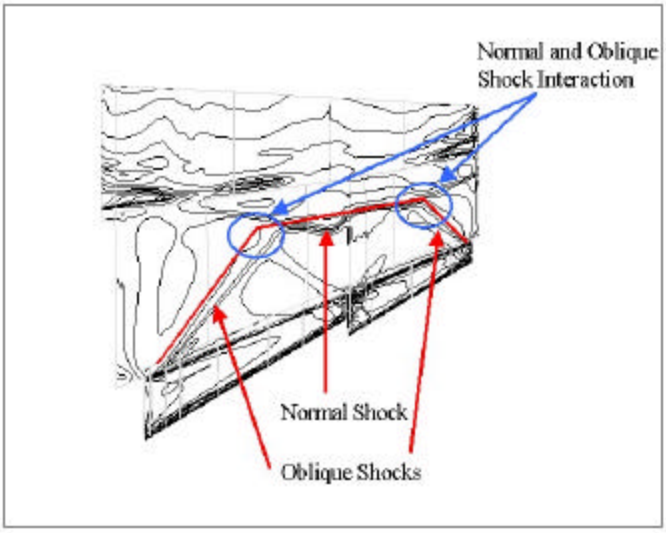

Figure 6. Oblique and Normal Shock Interaction

Taking into consideration all of the flow field features listed previously, eight chordwise stations where choosen to try and capture the crossflow topology for each of the flow field features at 6, 7, 8 & 10 degrees angle of attack. The stations were choosen such that the crossflow topology fore and aft of the oblique and normal shock interaction for each angle of attack could be observed. Stations were also choosen within the regions of separation such that the separation growth with angle of attack could also be observed. It was determined that the eight chordwise stations defined in Figure 7 were sufficient to make these observations.

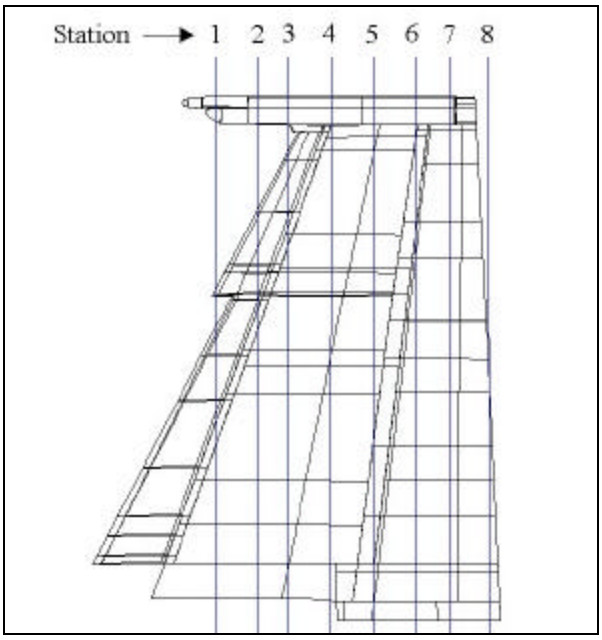

Figure 7. Definition of Chordwise Stations

3.4 Crossflow Traces in Detail

The separation contours shown in Figure 5 suggest that for the 6 degree case there is no separation present within Stations 1-4 however there is some separation within Stations 5-8. Plotting the crossflow velocity vectors, we can see in Figures 8 and 9 that the crossflow topology correlates with the separation contour. In Stations 1-4 the crossflow topology appears to be uneventful as the only singular points present are foci and nodes of attachment. These respectively translate to the Leading Edge Extension, LEX, vortex and the flow over the snag. Separation lines and complex singular point interaction presence are not seen. This suggests that the flow field is behaving in an orderly fashion and that the flow is remaining attached.

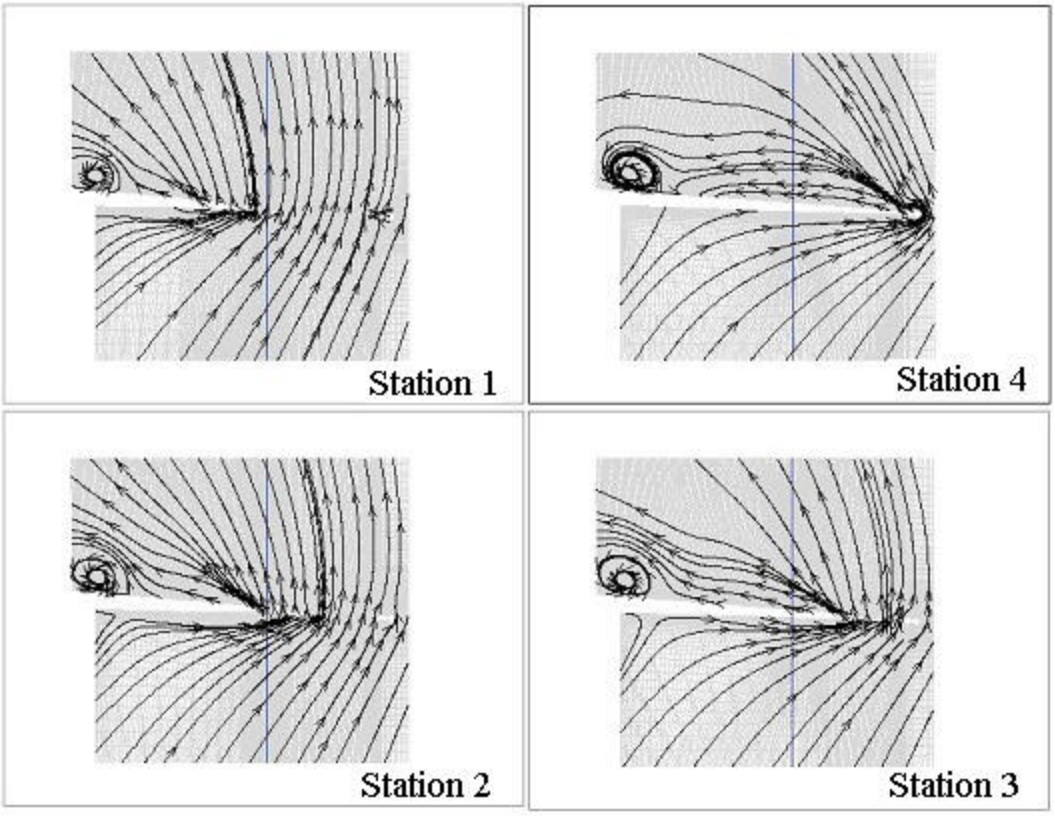

Figure 8. Crossflow Velocity Traces for AOA of 6 deg & M = 0.8 (Stations 1-4)

Observing the crossflow topology at Station 5 in Figure 9 shows just the opposite result. Singular points are located all over the crossflow. Station 5 shows a focus of attachment interacting with a node of separation. Between these two singular points is a saddle point in which a velocity line emerges which does not allow the skin friction lines from the nodal and focal point to cross. We have defined topological feature such as this in Chapter 2 and have

named it a line of separation, which is a necessary, but not a sufficient condition for separation. In this case, we see that this line of separation does in fact imply separation on the wing as the separation contour indicates it.

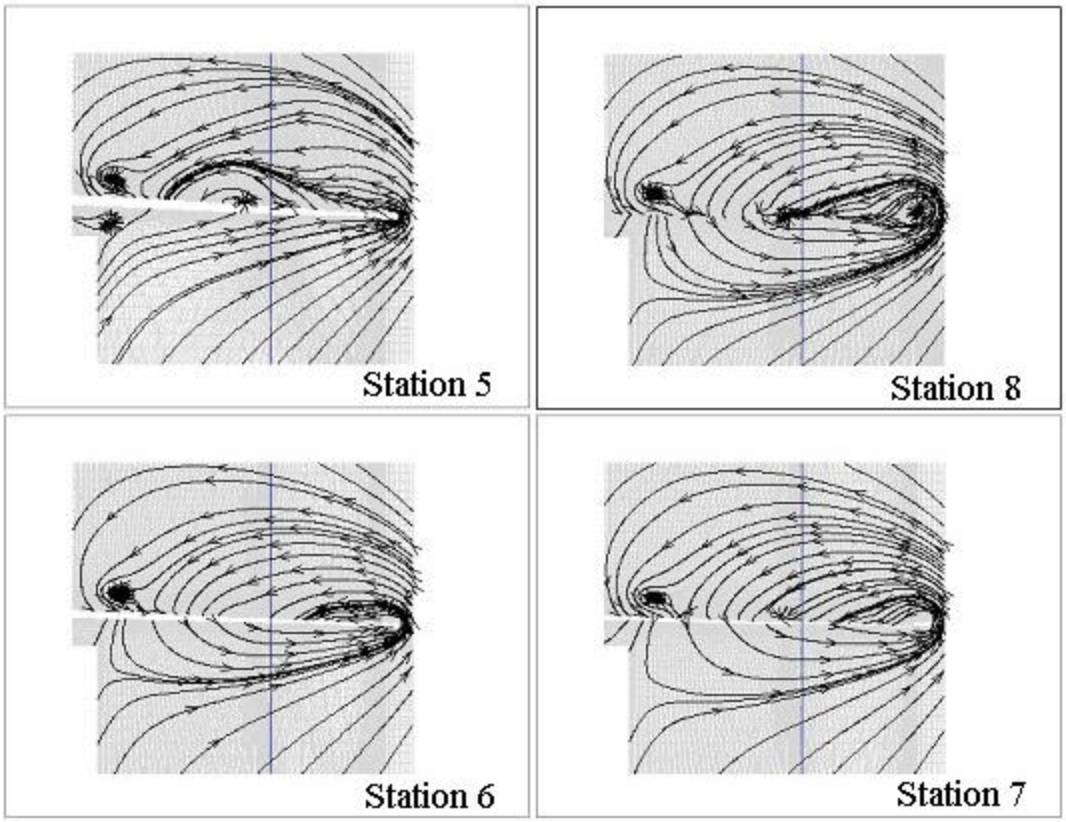

Figure 9. Crossflow Velocity Traces for AOA of 6 deg & M = 0.8 (Stations 5-8)

Stations 6-8 do not suggest anything in particular as there are not any complex singular point interactions as well as no lines of separation. However, they do suggest some questions. At all three stations, the crossflow appears to spill from the high pressure region under the wing to the low pressure area above the wing. This flow then curls and seems to end on the surface which is an impossibility because the flow has to go somewhere, although we must keep in mind that we are looking at a two-dimensional section of a three-dimensional flow thus the flow could be moving aft as well as curling into the wing. Thus, we can make no generalizations at this point about the crossflow in Stations 6-8 and its implications of separation. This topic will be addressed in Chapter 4.

The separation contour for the 7 degree angle of attack case implies that separation on the wing begins at about Station 3 and progresses through Station 8. Observing the crossflow

topology shown in Figure 10 suggests that the flow at Stations 1-2 is attached, as there are neither complex singular point interactions nor lines of separation. The crossflow topology appears to be behaving in an ordered fashion. The crossflow topology in Stations 3-4 appears to show a node of separation interacting with a focus of attachment. The velocity lines spilling over the tip of the wing from the high pressure lower surface to the low pressure upper surface are interacting with the focus of attachment possibly generated by the leading edge snag. A skin friction line emanating from a saddle point is preventing these lines from intersecting, thus creating a line of separation. Thus this crossflow topology agrees with the separation contour shown in Figure 5.

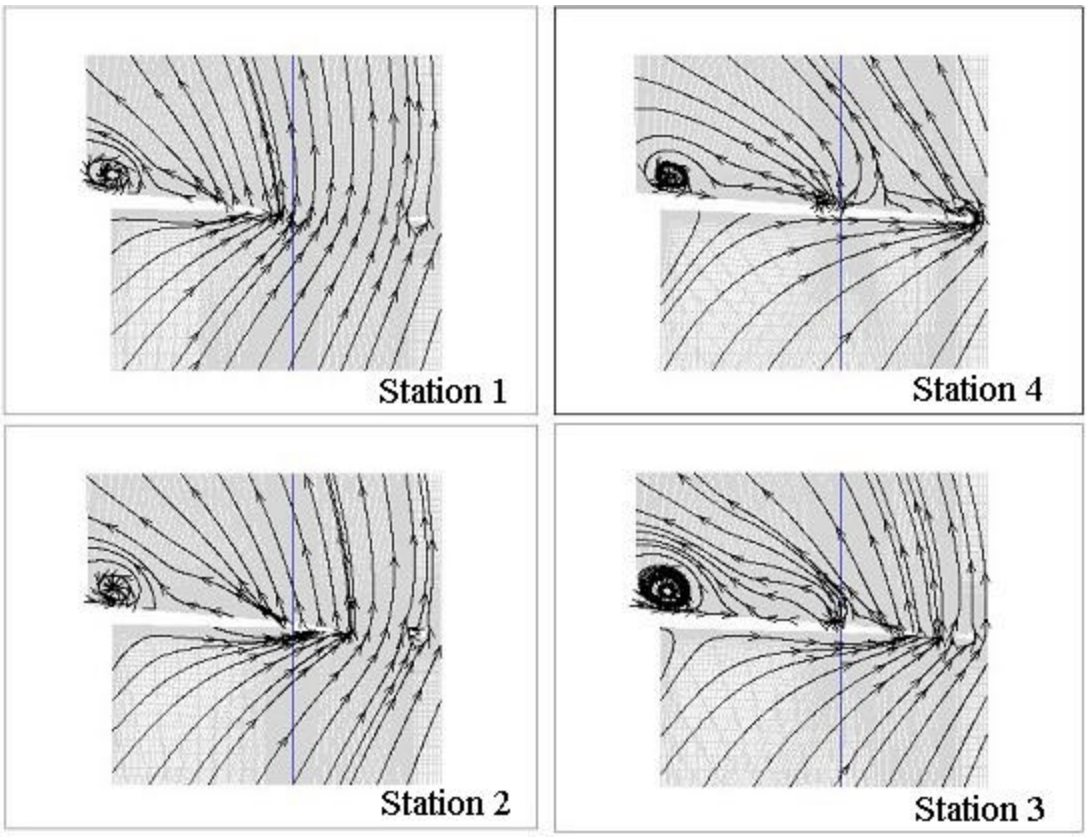

Figure 10. Crossflow Velocity Traces for AOA of 7 deg & M = 0.8 (Stations 1-4)

11 displays the crossflow topology at Stations 5-8. According to the separation contour, separation is present at each of the Stations. The crossflow topology in Stations 5 and 6 are quite similar as the flow over the tip of the wing is interacting with a focus near the center of the wing. These velocity lines are unable to cross because of a velocity line emerging from a saddle point. Thus a line of separation is present at each station. A line of separation is also present at Station 7. We see that velocity lines emerging from a saddle point near the center of the wing restrict the lines from a focus and a nodal point from crossing. The topology at Station 8 does not suggest

any separation as there are no lines of separation and no complex singular point interaction. This is contradictory to what the separation contour in Figure 5 indicates as it shows that separation is present.

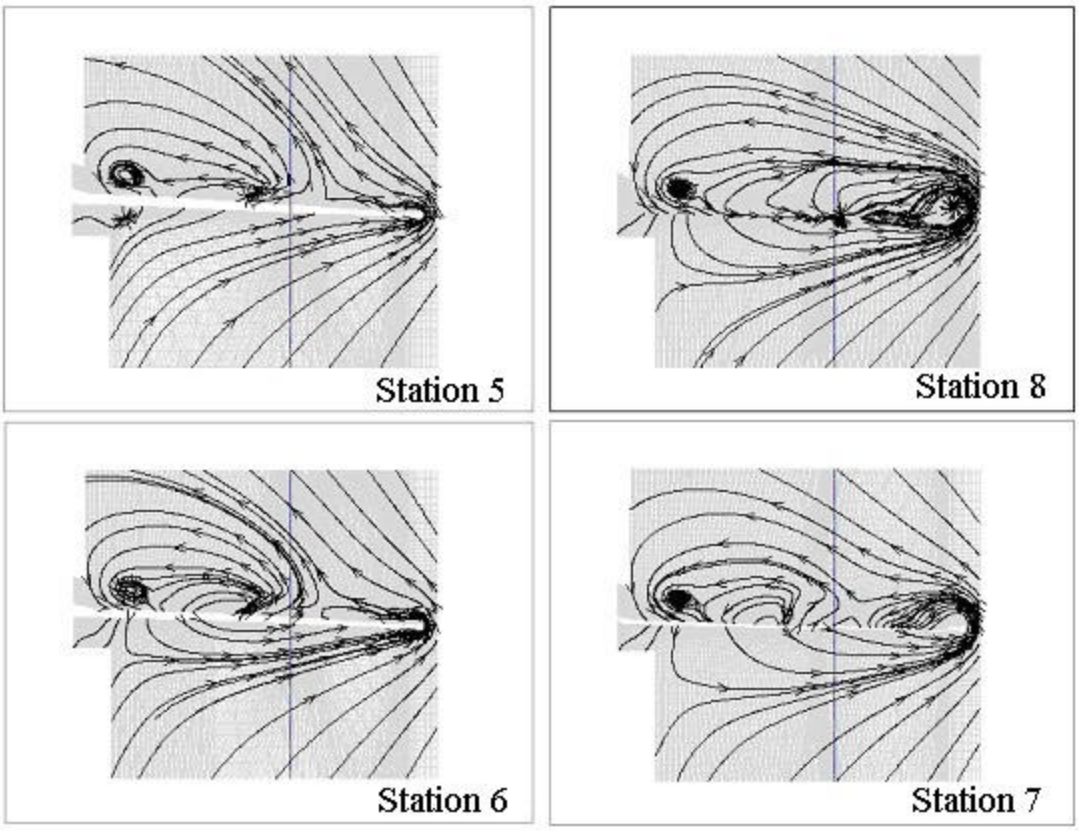

Figure 11. Crossflow Velocity Traces for AOA of 7 deg & M = 0.8 (Stations 5-8)

The separation contour for the 8 degree angle of attack case indicates that Stations 1 and 2 should not indicate separation. Flow topology as shown in Figure 12 agrees with this as there are no lines of separation or singular point interactions. Stations 3 and 4 however both show a line of separation on the outboard section of the wing. The topology shown at these stations looks very similar to that of the 7 degree case shown in Figure 9. There is a focus of attachment and a nodal point of separation separated by a saddle point, indicating that there is a line of separation. Thus we see again that the line of separation is a good indication that separation may be present.

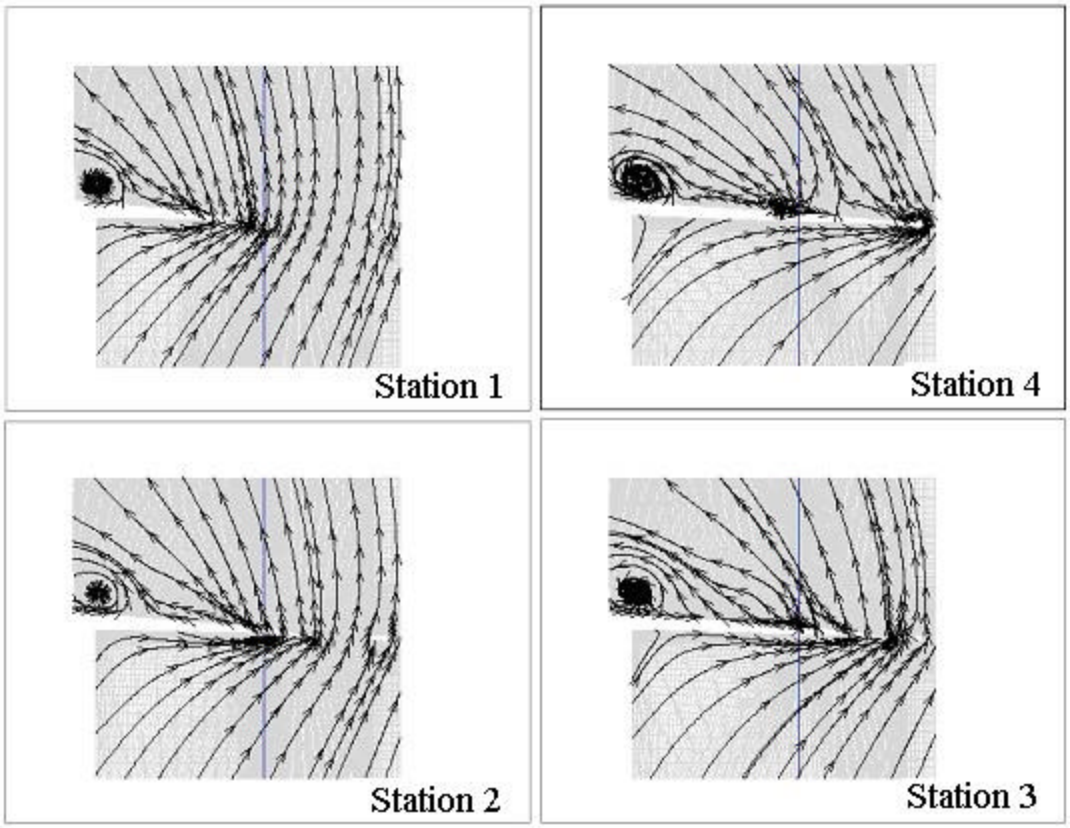

Figure 12. Crossflow Velocity Traces for AOA of 8 deg & M = 0.8 (Stations 1-4)

Figure 13 displays the crossflow topology at Stations 4-8 for the 8 degree angle of attack case. The topology agrees with the separation contour as separation is evident at all of the Stations. Stations 5,6 and 7 all have a line of separation along with secondary flows. Just under the line of separation there appears to be a focus of separation on the surface. This translates into the small region of the flow curling under itself forming a secondary vortex just outboard of the snag. The formation of this secondary vortex usually is accompanied by separation. Figure 5 agrees with this as it shows a region of separated flow on the outboard section of the wing.

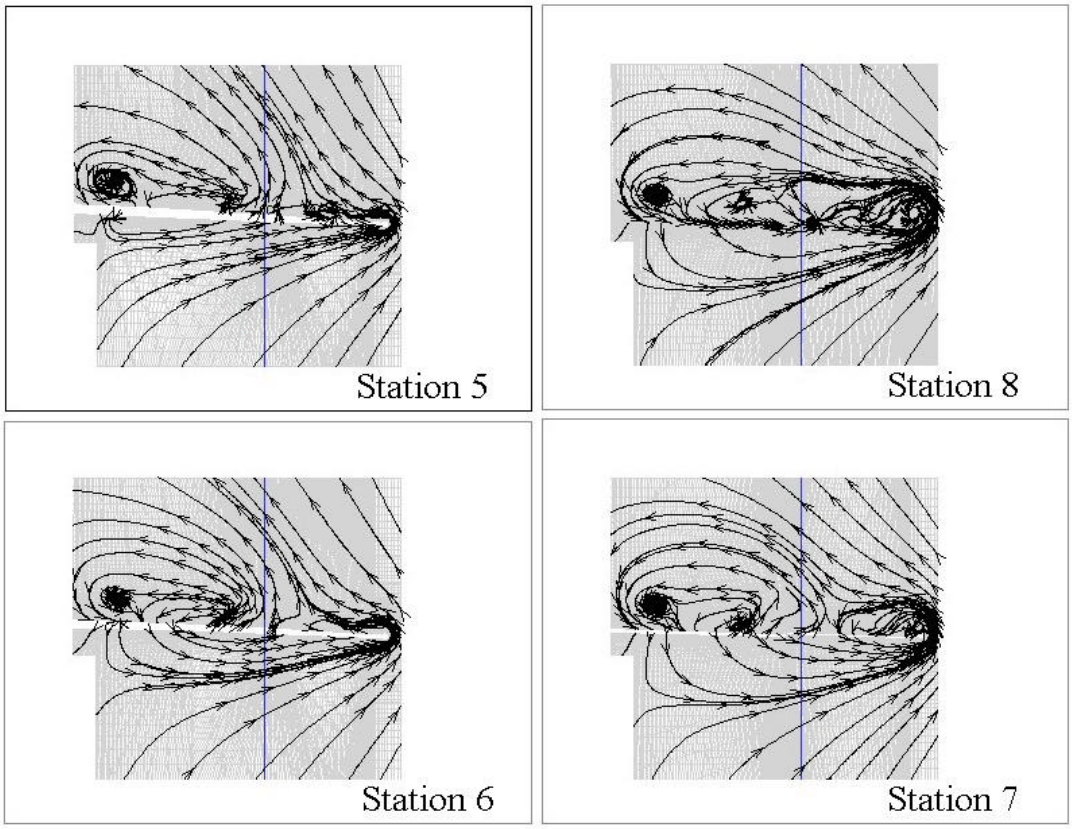

Figure 13. Crossflow Velocity Traces for AOA of 8 deg & M = 0.8 (Stations 5-8)

As one might expect, the topology for the 10 degree angle of attack looks very similar to that of the 7 and 8 degree cases. Figure 14 shows the crossflow topology for Stations 1-4. These traces show that the flow has developed in an ordered fashion in Stations 1 and 2 as the only singular points are a nodal point of attachment and a focus of separation. These respectively translate to the flow spilling over the snag from the high pressure lower surface to the low pressure upper surface and the LEX vortex. Stations 3 and 4 show a line of separation located between the mid section of the wing and the wing tip. The separation contour for this case agrees with the topology interpretation as separation is present on the wing at Stations 3 and 4.

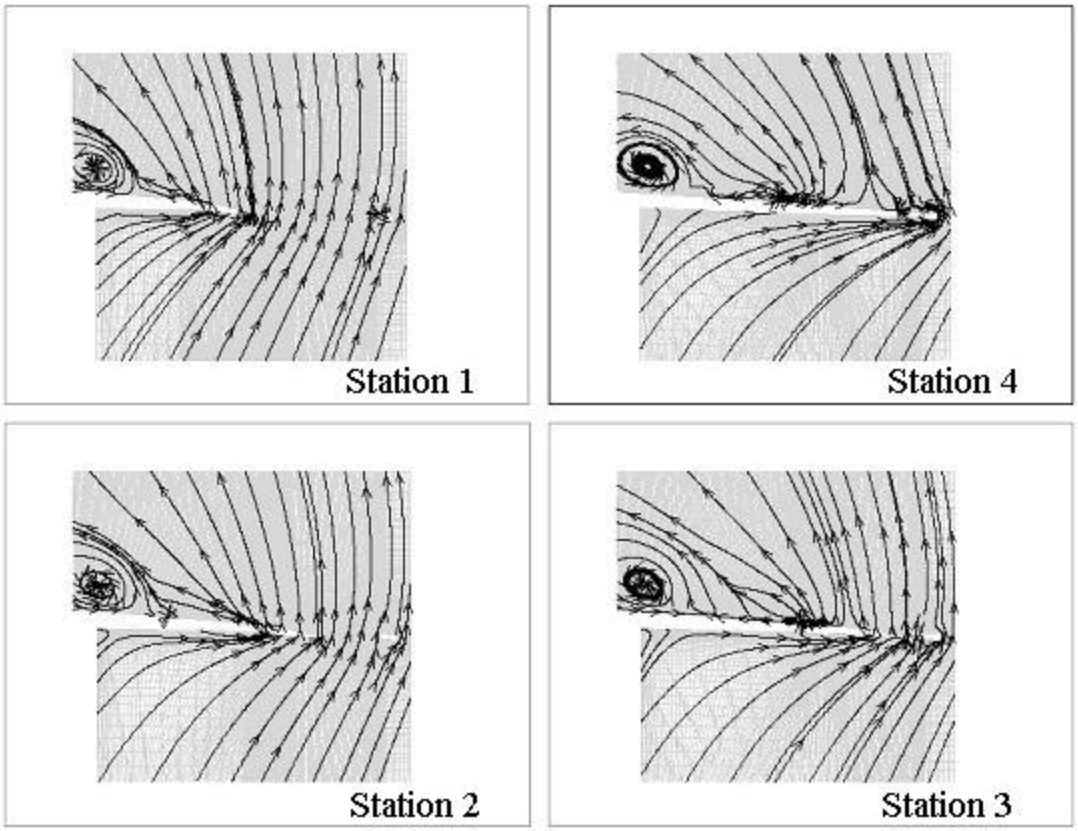

Figure 14. Crossflow Velocity Traces for AOA of 10 deg & M = 0.8 (Stations 1-4)

Stations 5-7, as shown in Figure 15, for the 10 degree angle of attack case, each show a line of separation which emerges from a saddle point which agrees with the separation contour, as it is present at the same location as separation. Station 8 shows complex interaction between nodal, saddle and foci points at the tip of the wing. If one investigates the separation contour of Figure 5 carefully, there is a small region of separated flow at the tip towards the trailing edge of the wing. There is not enough evidence to hypothesize if this topolgy directly relates to separation.

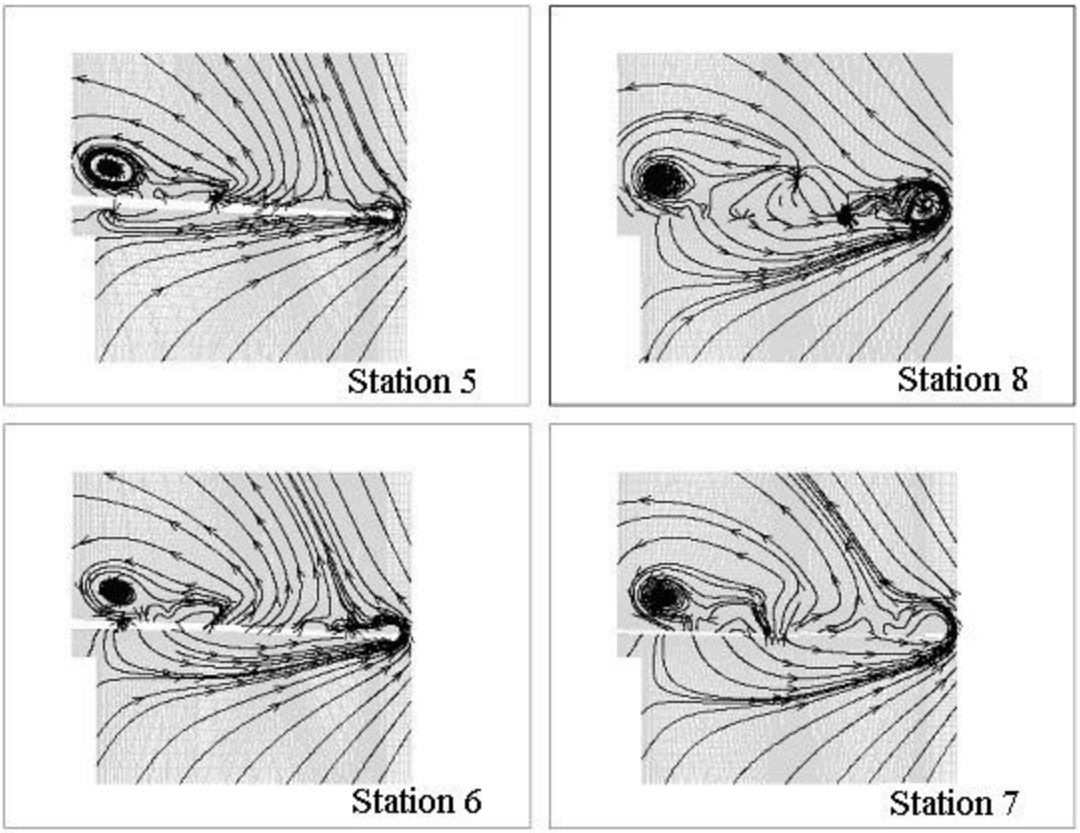

Figure 15. Crossflow Velocity Traces for AOA of 10 deg & M = 0.8 (Stations 5-8)

3.5 Conclusions from Crossflow Velocity Traces

Investigating the crossflow velocity traces for four different angles of attack at eight chordwise stations has proven fruitful. It has been verified that a line of separation in the crossflow is an indication that separation may be present on the surface of the wing. Furthermore, shocks complicate the crossflow as it was seen in all of the cases that the crossflow just aft of a shock becomes much more complex. New singular points appear and interactions between singular points are seen. As the angle of attack is increased the flow topology changes critically only in the change from 6 to 7 degrees. This is the range in angle of attack in which the shock jumps rapidly forward so it may be postulated that for this wing the flow topology is more sensitive to shock location as opposed to angle of attack. Comparing the topology between the 7, 8 and 10 degree cases, supports this hypothesis as the topology is similar before and after the shock for each case. The flow topology for each case before of the shock is much different then the topology just aft of the shock.

Chapter 4 Investigation of Off-the-Surface Streamtraces

4.1 Off-the-Surface Streamtraces

If one were to look down onto a wing and plot the axial and spanwise velocity components, *u* and *w*, at various heights above the wing these would be considered off-the-surface streamtraces. This was done for each of the 6, 7, 8 and 10 degree angle of attack cases at heights ranging from approximately on the surface to about one foot off the surface. The streamtraces were laid on top of a separation contour for the corresponding height. Again, the blue region indicates attached flow where the red region is used to display areas of separated flow. It must be noted that for the 6 degree case that there were no singular points just off the surface so they will not be presented here.

4.2 Off-the-Surface Grid and Data Generation

Amtec Tecplot was used to generate the off-the-surface grids and data. The imbedded Tecplot Slice function was used to extract 2-D planes out of the 3-D grid. The Slice function interpolates the data points in the grid to create a 2-D plane at a specified position on, in this case, the y-axis. Data for this grid, the x and w components of the velocity vector was calculated by dividing out the density from the momentum vector in the CFD solution files. Tecplot also has a streamtrace function that allows the user to plot 2-D vectors. This was taken advantage of to plot the off-the-surface streamtraces using the *u* and *w* components of velocity as the vector variables.

4.3 Investigation of Off-the-Surface Streamtraces

Figure 16 displays the off-the-surface streamtraces approximately on the surface for an angle of attack of 7 degrees and at Mach number of 0.8. Starting inboard and moving outboard the singular points will be identified. First, there appears to be a nodal point of separation at about midchord of the wing which is a consequence of the LEX vortex interacting with the freestream flow. The rest of the singular points appear aft of the snag and from midwing to the trailing edge. Two foci of separation are located within the region of separation. These both feed into saddle points. From the saddle points emerge a line which feeds to a nodal point of separation, not letting the lines from the node cross. Thus there are two lines of separation, one at the beginning of the separated region furthest outboard and the other at the end of the separated region furthest inboard. It appears that the separation lines not only indicate that separation is present but may also be an indication of the location of the separated region. This will be investigated further as more cases are observed.

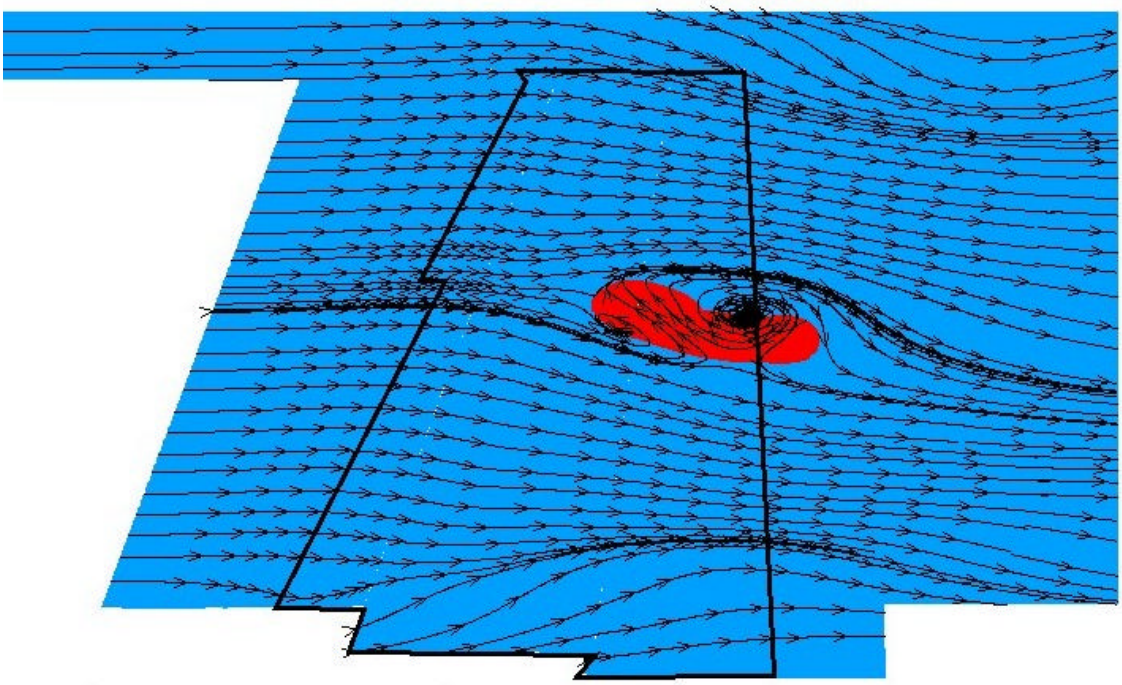

Figure 16. Off-the-Surface Streamtrace for AOA of 7 deg & M=0.8 (approx on the surface)

The off-the-surface streamtraces for the 8 degree angle of attack case are shown in Figure 17. As expected, the LEX vortex is still present, represented by the flow turning outboard at the most

inboard section of the wing. Just aft of the snag, there are a number of singular points. First we see a focus of separation and a saddle point which feed to a line of separation. These are located aft of the snag in the separated region closest inboard. Moving outboard, there is a focus of attachment and a nodal point of separation. The nodal point is located in the center of the red region and the focus is present just in front of the trailing edge of the wing. Finally, aft of the snag at midchord there is a saddle point and a focus of separation. These two singular points interact and form a line of separation. Again we see two lines of separation, one along the most outboard section of the separation region and the other along the most inboard section of the separated region.

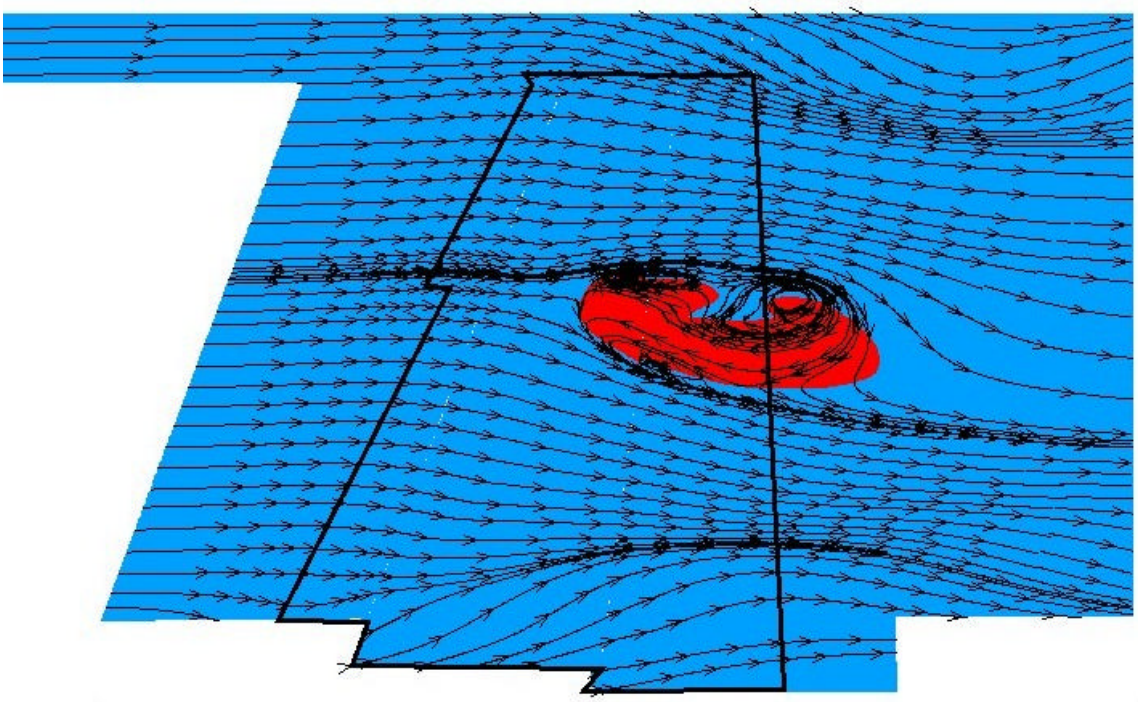

Figure 17. Off-the-Surface Streamtrace for AOA of 8 deg & M=0.8 (approx. on surface)

As we move off the surface approximately 0.25 feet for the 8 degree case, we see in Figure 18 that flow field has simplified drastically however there are still singular points present. At the trailing edge of the wing on the most inboard section of the separated region a saddle point is present. Just aft of the saddle point is a nodal point of separation. These two singular points form a line of separation. A focus of attachment is located right at the trailing edge of the wing along the boundary of the separated region. Directly in front of the focus is a nodal point of separation

but no saddle point or line of separation. This case has shown one line of separation along the most inboard region of separated section but none on the outboard region.

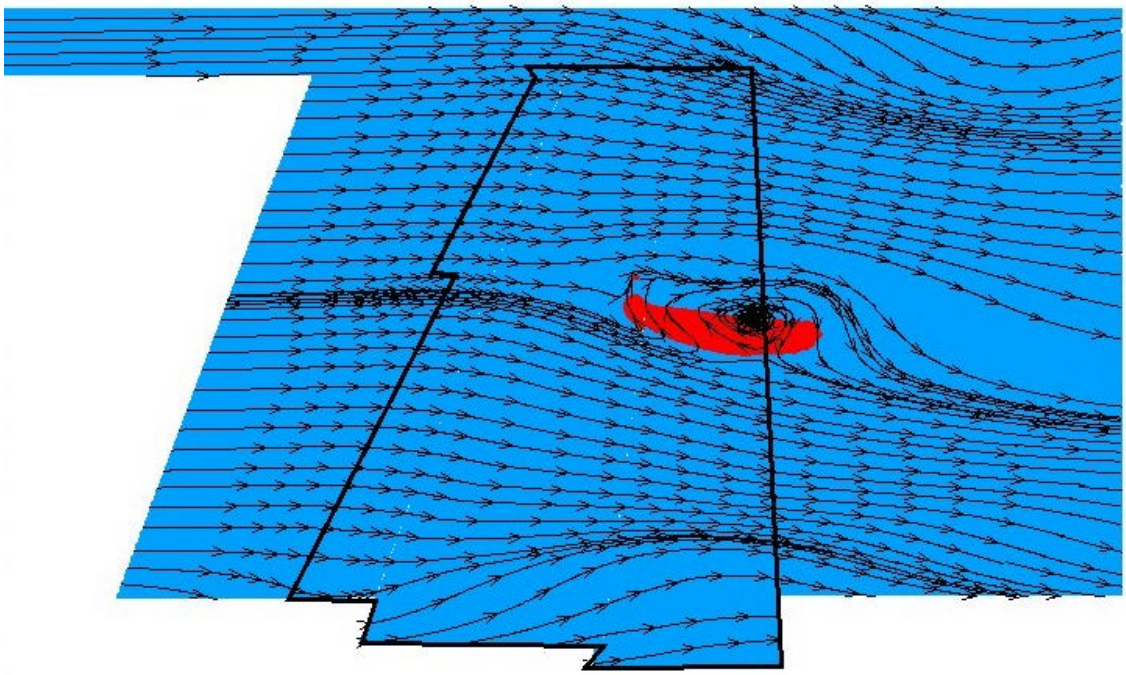

Figure 18. Off-the-Surface Streamtrace for AOA of 8 deg & M=0.8 (approx. 0.25 ft off the surface)

For the 10 degree case there are many singular points when looking at the off-the-surface streamtraces. While invesigating the streamtraces approximately on the surface as seen in Figure 19, it is apparant the separation region has grown tremendously from the lower angles of attack. The LEX vortex and it's corresponding nodal point of separation is present on the inboard section of the wing. Two foci of attachment separated by a saddle point are present along the most inboard section of the separated region. These singulare points along with a nodal point of separation located just ahead of the first focus form a line of separation along the inboard border of the separated region. Just aft of the snag at about midchord there lies a nodal point of separation. Further aft on the trailing edge a large focus of attachment is located. Looking in the wake just aft of the focus is a saddle point. The lines emerging from the focus and nodal point are prevented from crossing because of the presense of a line emerging from a saddle point located in the wake. Thus there is a line of separation on the outboard separated region. The lines of separation in this case indicate the size and location of the separated region.

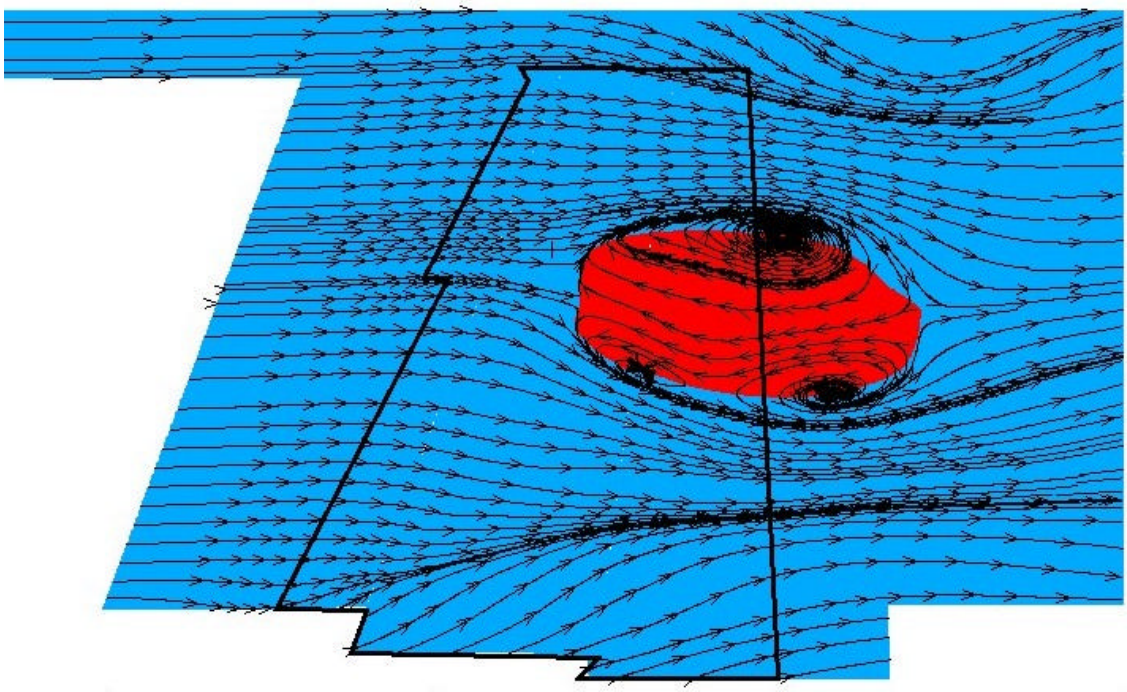

Figure 19. Off-the-Surface Streamtrace for AOA of 10 deg & M=0.8 (approx. on the surface)

The streamtraces at a height of approximately 0.25 feet off the surface for the 10 degree angle of attack case are seen in Figure 20. These streamtraces look very similiar to those in Figure 19. The topology is virtually identical, only the foci are not as large. The same two foci of attachment separated by a saddle point which feed a line of separation are present. Looking further outboard on the wing, there is a nodal point of separation just aft of the snag at about midchord. This nodal point feeds into a focus of separation. Aft of the focus of separation is another nodal point however it is of the attachment type. A saddle point in the wake at the furthest aft area of the separation prevents the lines from the nodal point and focus from crossing so we have another line of separation. Again, we see a line of separation on the furthest outboard and inboard area of the separated region.

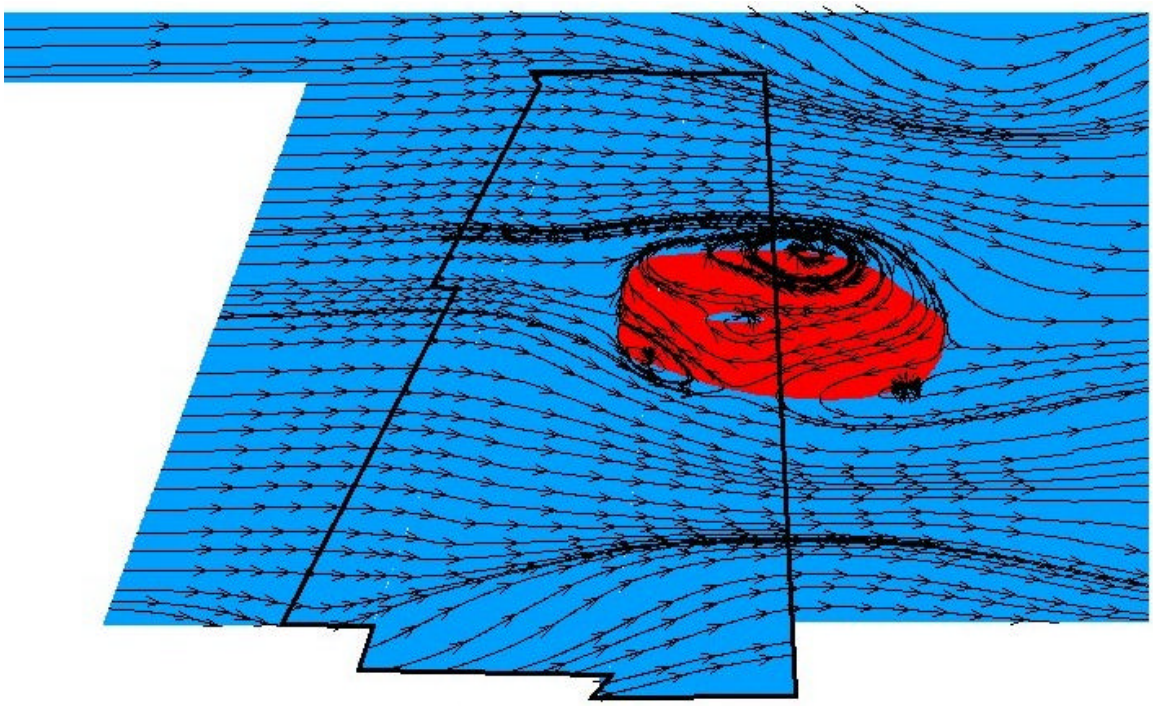

Figure 20. Off-the-Surface Streamtrace for AOA of 10 deg & M=0.8 (approx. 0.25 ft off the surface)

Figure 21 shows the off-the-surface streamtraces for the 10 degree angle of attack case approximately 0.5 feet off the surface. There are three singular points present, a saddle point at the most inboard section of the separated region and two foci of separation, one located on the trailing edge aft of the snag and one just outboard of the latter in the wake. Freestream lines just outboard from the focus in the wake are sucked inboard and are reversed. The other focus further pulls these lines inboard until the inboard freestream lines pull the flow back and try to straighten it out. These lines are prevented from crossing by the saddle point mentioned earlier and a line of separation emerges on the inboard region of the separated flow.

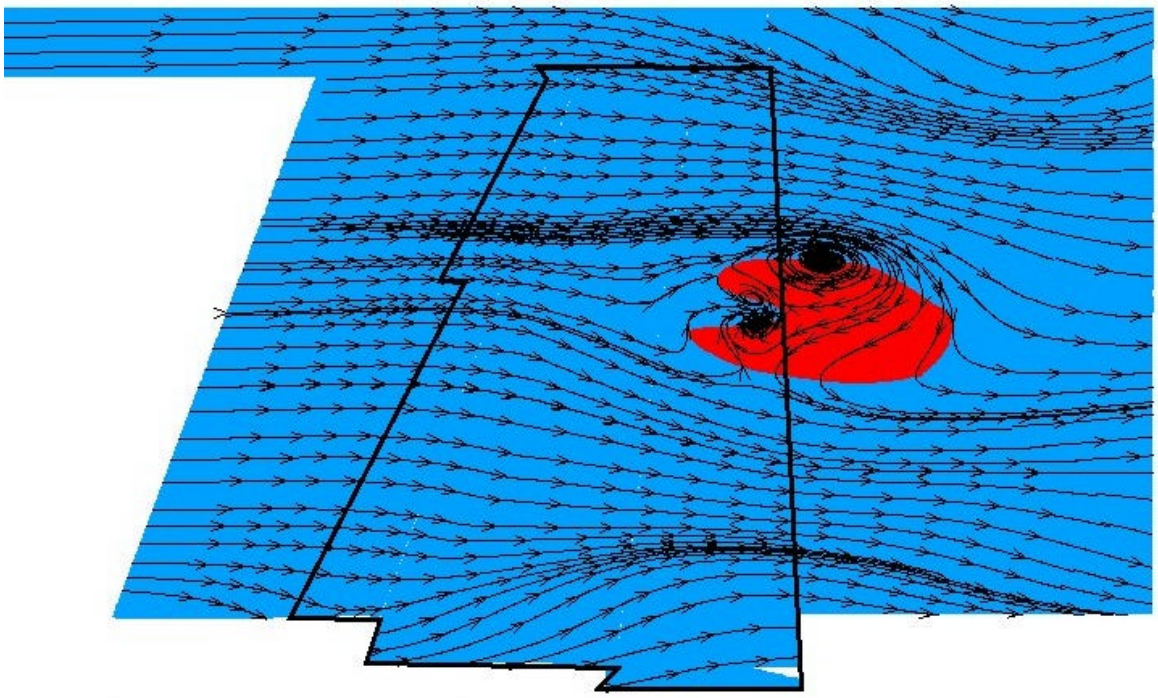

Figure 21. Off-the-Surface Streamtrace for AOA of 10 deg & M=0.8 (approx. 0.5 ft off the surface)

Once moving to 0.75 feet off the surface for the 10 degree angle of attack case as seen in Figure 22, the flow simplifies drastically. Here all of the singular points are located in the wake of the wing. There is a nodal point of separation located inboard of the snag just off the trailing edge. Moving inboard, there is a saddle point directly aft of the snag on the trailing edge. The saddle point separates the nodal point and a focus of separation which is located just outboard of the snag in the wake. Lines from the nodal point and focus are prevented from crossing because the saddle point thus a line of separation is also present along the most inboard area of the separated region.

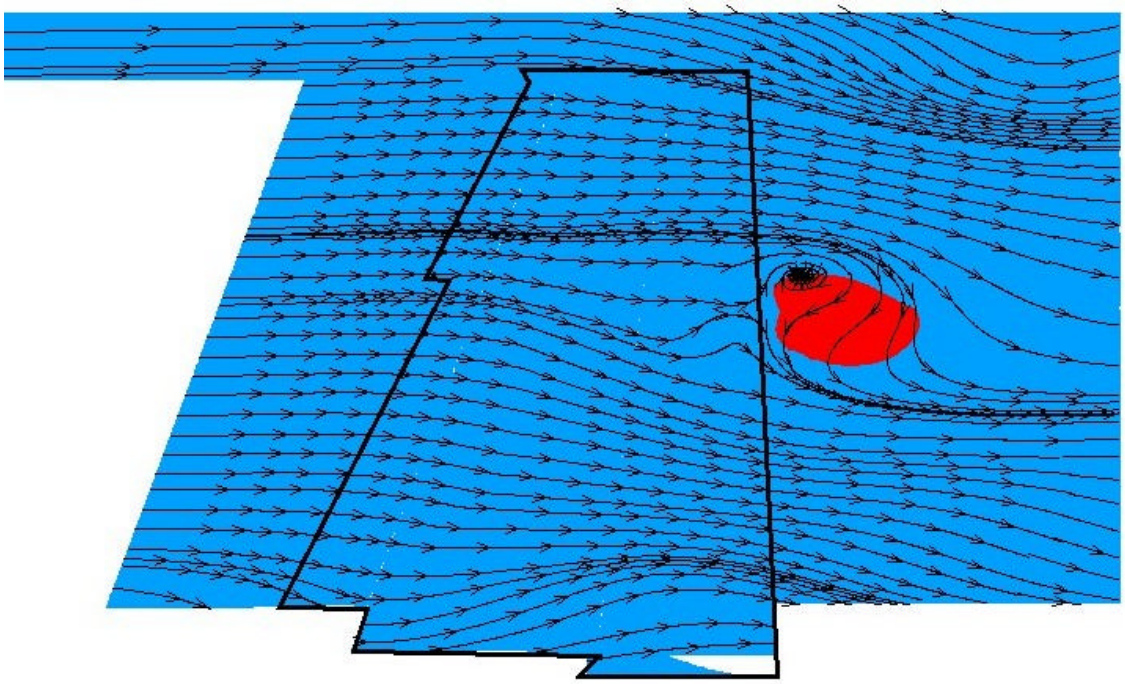

Figure 22. Off-the-Surface Streamtrace for AOA of 10 deg & M=0.8 (approx. 0.75 ft off the surface)

4.4 Conclusions from Off-the-Surface Streamtraces

Investigating the off-the-surface streamtraces have shown that as angle of attack is increased the area of separated flow not only grows but also becomes more complex. For the 6 degree angle of attack case, the region of separated flow was concentrated to the surface and as one moved off the surface the flow returned entirely to the axial direction. This was also the case for the 7 degree angle of attack case only the flow did not return uniform until after one moved approximately 0.25 feet off the surface. As the angle of attack was increased, the distance off the surface in which separation of the flow did not occur increased. Furthermore, as angle of attacked was increased the number of singular points and their intensity grew.

It was also verified that in all of the cases investigated the presence of a line of separation was an indication of separation. Moreover, in all but two cases there were two lines of separation. One located along the furthest outboard and inboard area of the separated region. No lines of separation were observed in or around attached flow, thus the lines of separation may not only indicate that separation is present but in fact give a location for the separated region.

Chapter 5 Conclusions

Flow topology off-the-surface and in the crossflow has been investigated and discussed for angles of attack of 6, 7, 8 and 10 degrees for a moderately swept wing at a Mach number of 0.8. An Investigation of crossflow velocity traces at eight chordwise stations has proven fruitful. It has been verified that a line of separation in the crossflow is an indication that separation may be present on the surface of the wing. Furthermore, shocks complicate the crossflow as it was seen in all of the cases that the crossflow just aft of a shock becomes much more complex. New singular points appear and interactions between singular points are seen. It may be postulated that for this wing the flow topology is more sensitive to shock location as opposed to angle of attack.

Investigating the off-the-surface streamtraces has shown that as angle of attack is increased the area of separated flow not only grows but also becomes more complex. For lower angles of attack, the region of separated flow was concentrated near the surface and as one moved off the surface the flow returned entirely to the axial direction. As the angle of attack was increased, the distance off the surface in which separation of the flow did not occur grew larger. Furthermore, as angle of attacked was increased the number of singular points and their intensity grew. It was also verified that in all of the cases investigated the presence of a line of separation was an indication of separation. Moreover, the lines of separation may not only indicate that separation is present but in fact give a location for the separated region.

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Appendix A

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Cipolla, K.M. and Rockwell, D., "Instantaneous Crossflow Topology on a Delta Wing in Presence of Vortex Breakdown," *Journal of Aircraft*, Vol.35, March 1998, pp. 218-222.

> Cipolla and Rockwell present their investigation of crossflow structure of the leading-edge vortices on a delta wing with the use of particle image velocimetry. They compare instantaneous images to characterize the transformation of the streamline topology as the vortex breakdown position moves upstream or downstream of its nominal value.

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